

# 聆听天籁

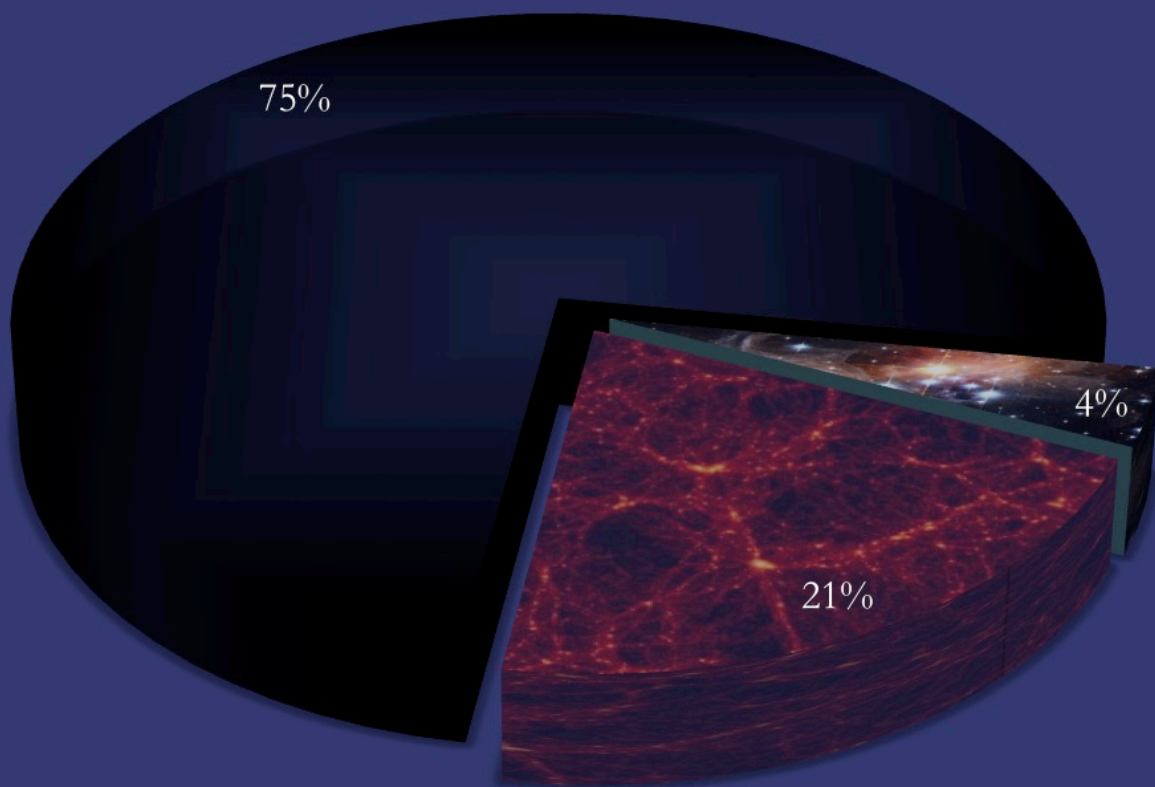
## 暗能量的射电探测

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中国科学院国家天文台

2011.4.1 中国科技大学

# 宇宙的组分



■ 普通物质

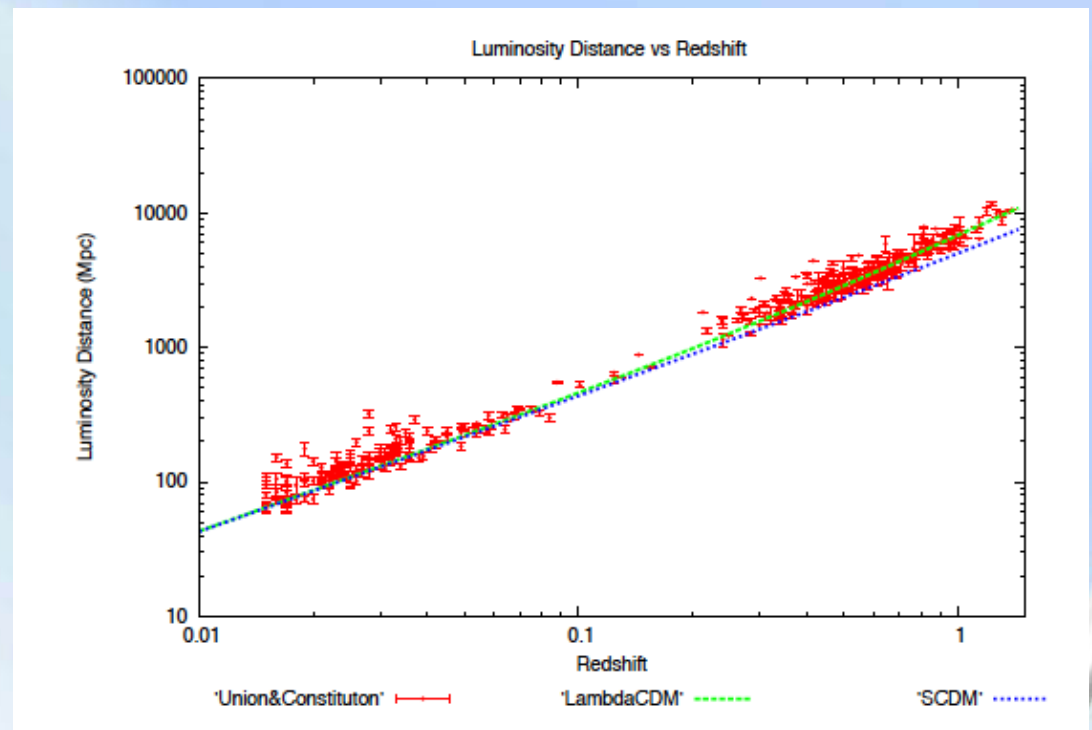
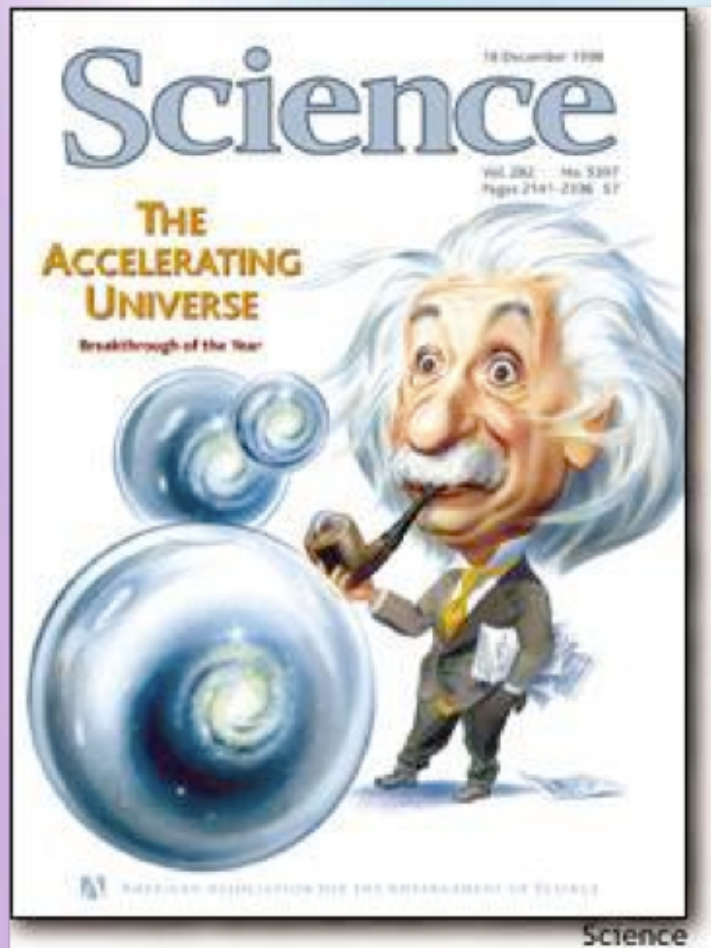
■ 暗物质

■ 暗能量

# 宇宙加速膨胀与暗能量

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

dark energy:  $\rho > 0$ ,  $p < -\rho/3$



# 解决暗能量问题的关键： 暗能量状态方程与膨胀历史

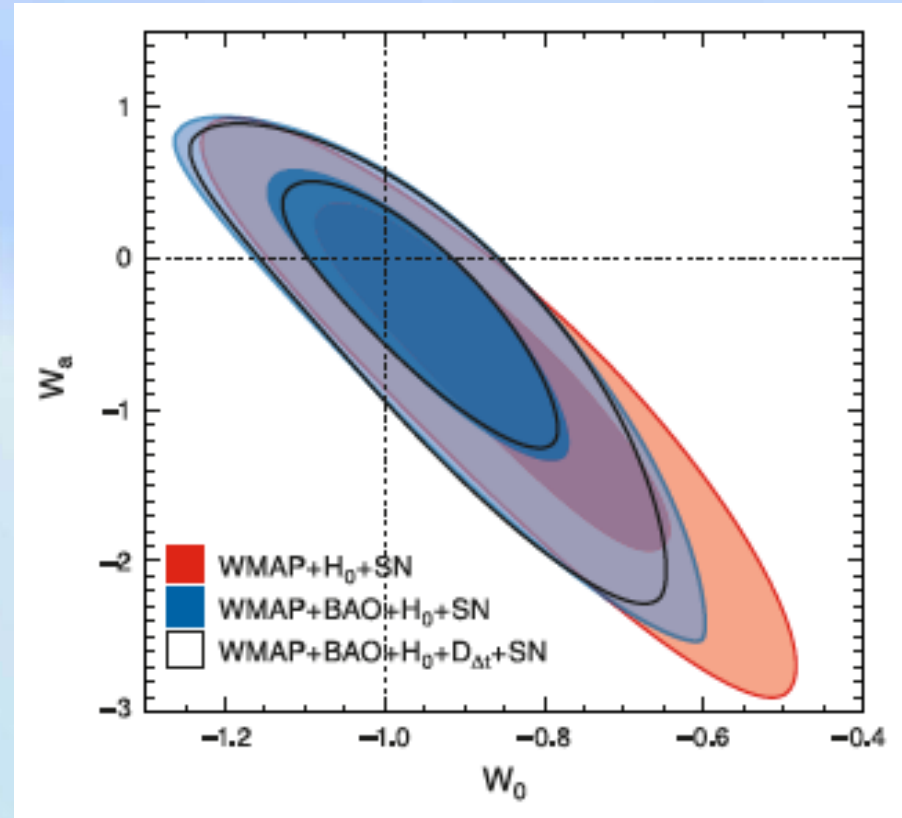
$$p = w\rho$$

状态方程的一种参数化形式：

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

宇宙膨胀历史与暗能量状态参数：

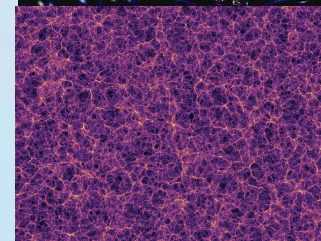
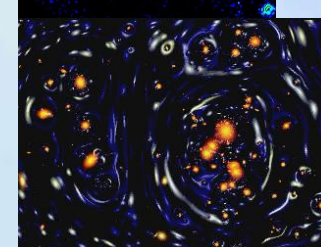
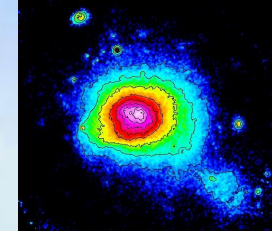
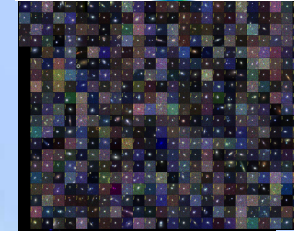
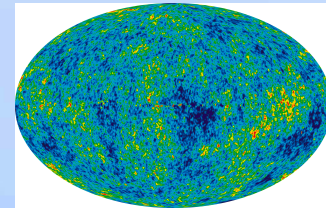
$$\frac{H(z)}{H_0} = \left[ \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_X e^{3 \int_0^z \frac{1+w(z)}{1+z} dz} \right]^{1/2}$$



Komatsu et al. 2010

# 暗能量观测的手段： 突破口在哪里？

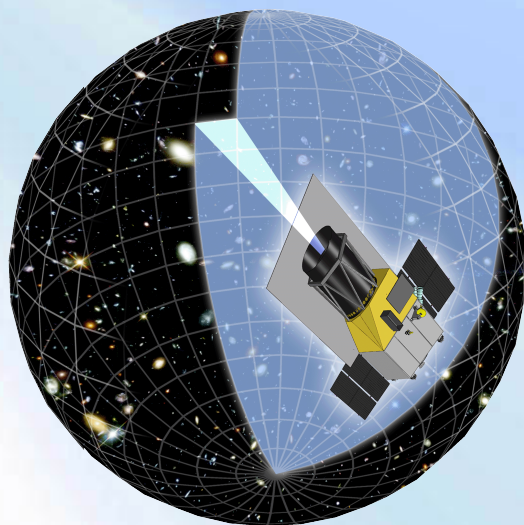
- CMB: Planck 卫星可达到宇宙方差，未来改进余地不大
- 超新星：未来几年内Ia 超新星样本可超过1000颗，依赖经验规律，系统误差将成为主要制约因素
- 星系团计数：依赖经验规律，系统误差是主要问题，观测方面利用X-ray或SZ效应
- 弱引力透镜：物理清楚，系统误差比较小，观测要求大视场、高角分辨率、高星等极限
- 重子声波振荡：物理清楚，系统误差比较小，观测要求大视场和红移信息



# 国际上探测暗能量的一些重大项目

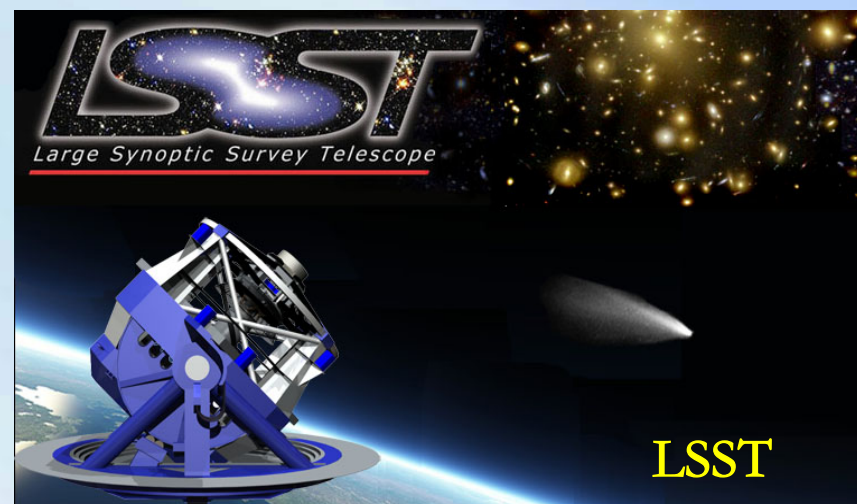
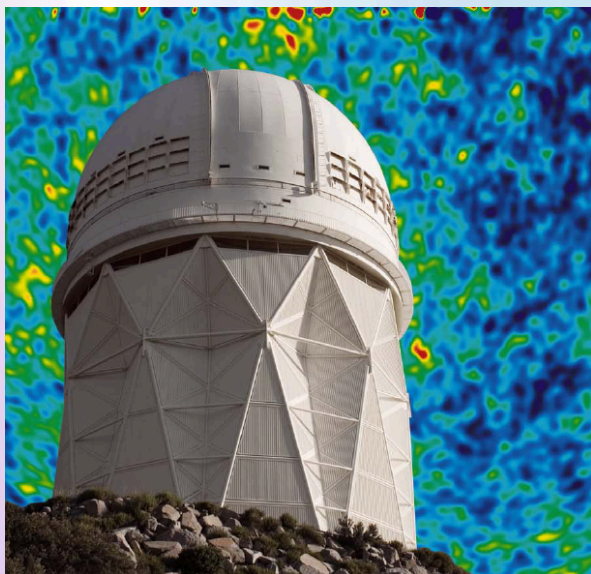
参照美国Astro2010 report: 大部分重大实验在2020年左右开始

Euclid



WFIRST

BigBOSS



LSST

# 中国可用于探测暗能量的项目

已立项的项目：

LAMOST

FAST

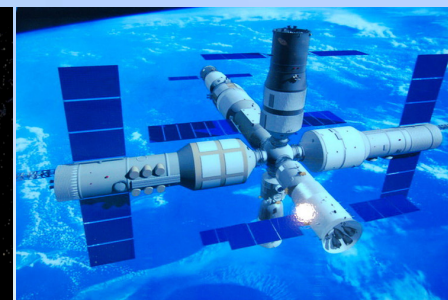
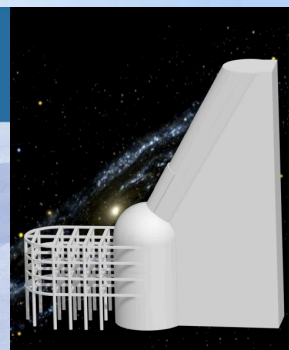


讨论中的项目：

南极光学望远镜(2m?)

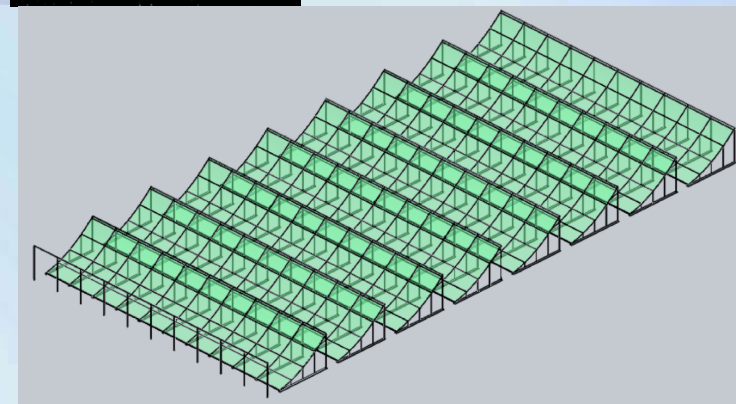
南天LAMOST(4m?)

天宫空间站望远镜(2m)



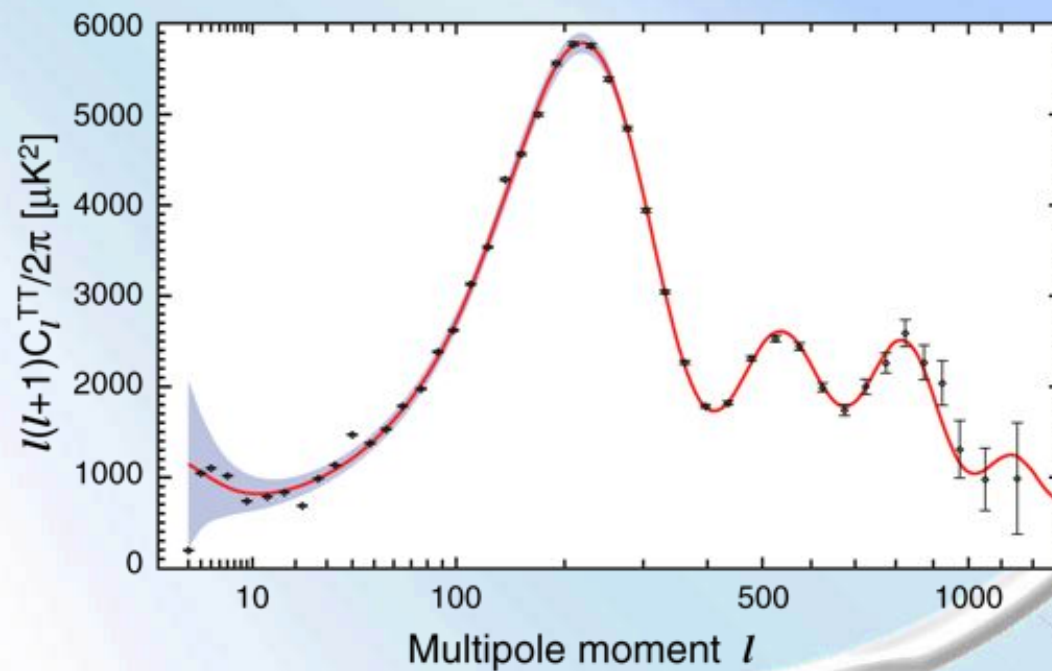
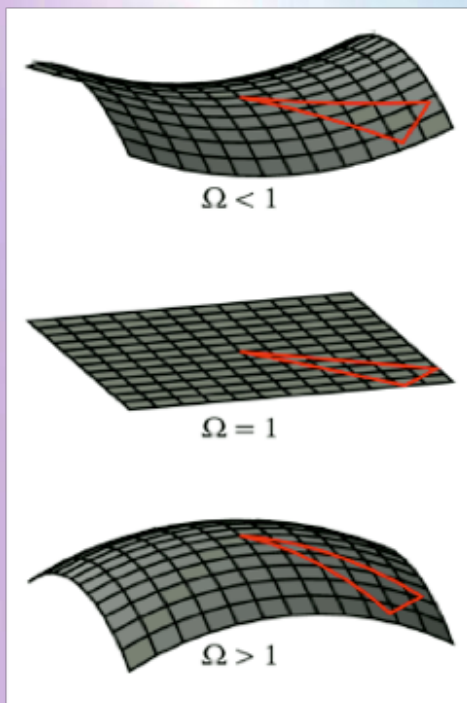
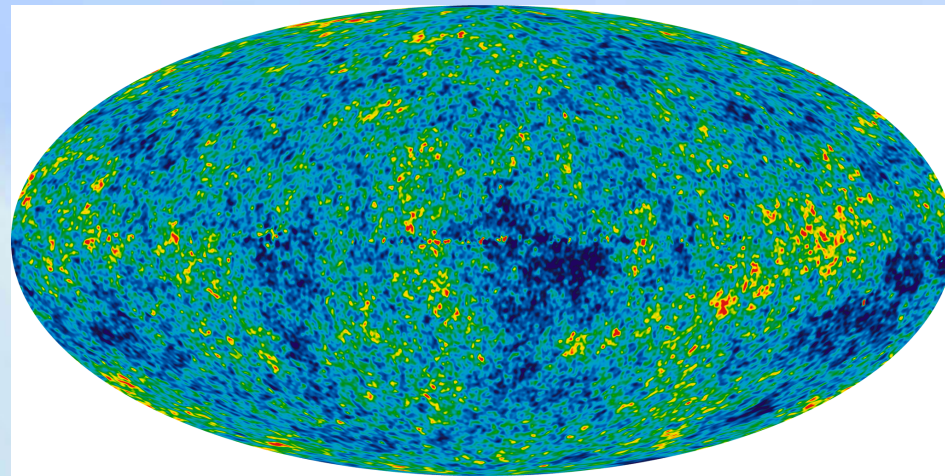
一个新的设想：

射电探测暗能量



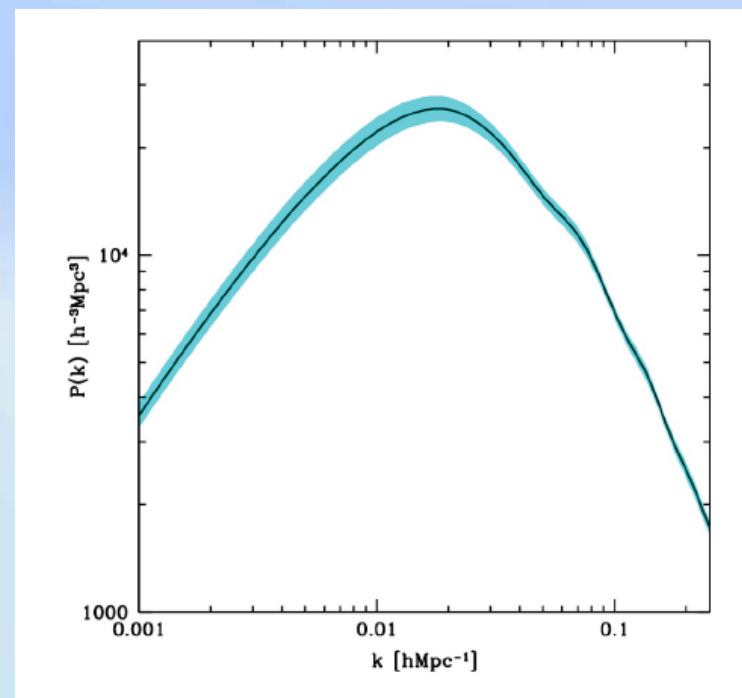
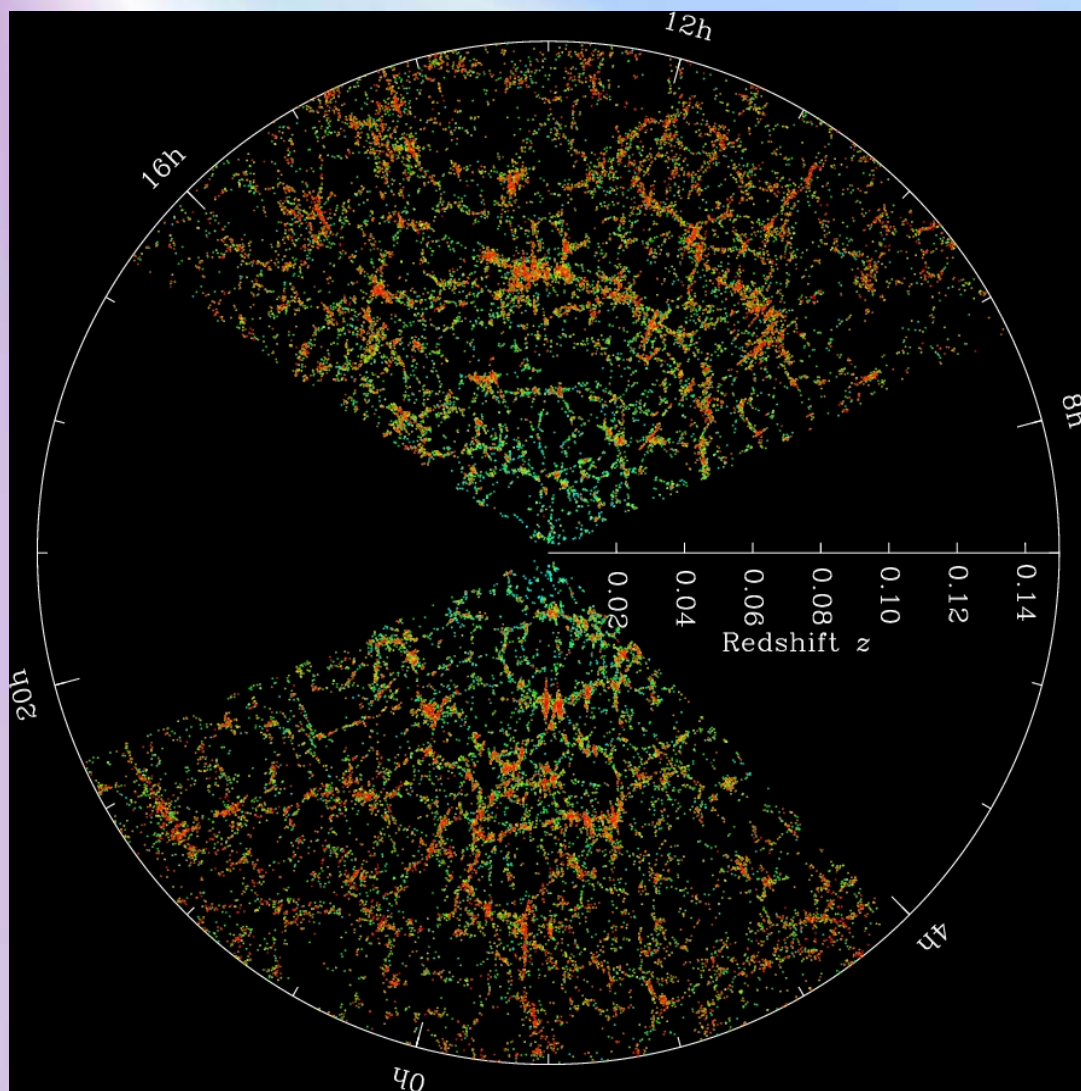
# CMB中的声波振荡

根据宇宙早期的“声音”，  
可以确定宇宙几何！





# 大尺度结构



# 大尺度结构中的重子声波振荡 (baryon acoustic oscillation, BAO)

大尺度结构功率谱中的径向和横向  
BAO振荡特征可测：

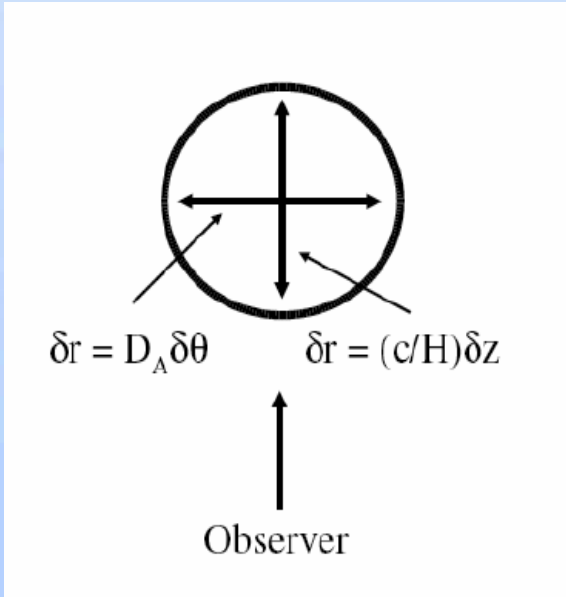
哈勃膨胀率  $H(z)$

角直径距离  $d_A(z)$

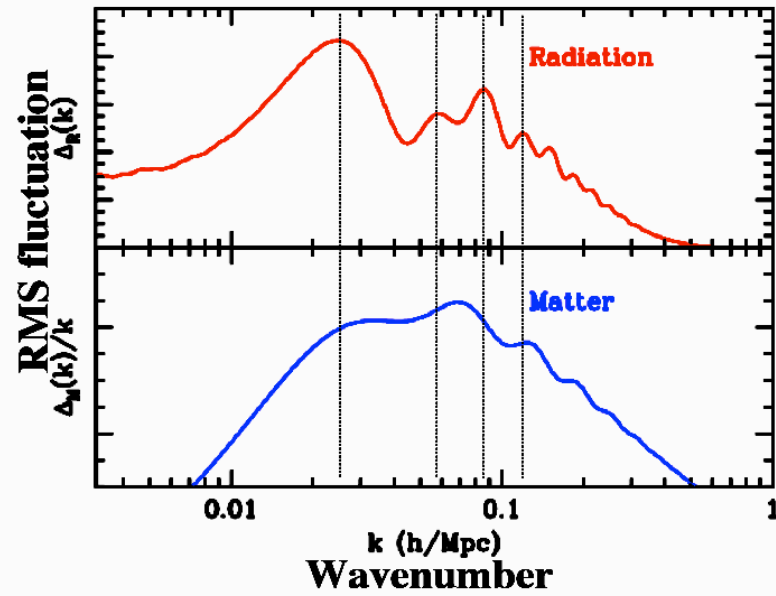
$$r_{\parallel} = \frac{c\Delta z}{H(z)}$$

$$r_{\perp} = (1+z)D_A(z)\Delta\theta$$

$$D_A(z) = \frac{c}{1+z} \int_0^z \frac{dz}{H(z)}$$

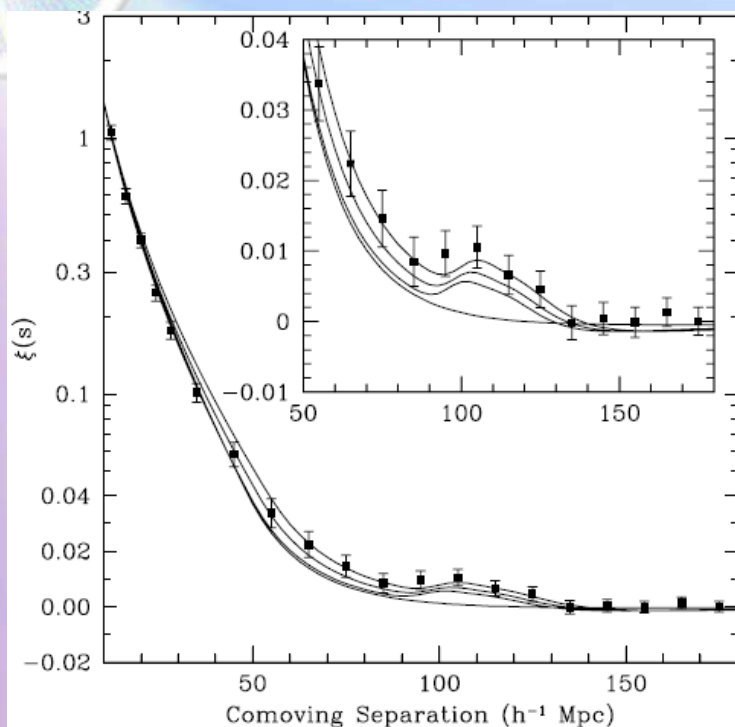


Baryon (acoustic) oscillations

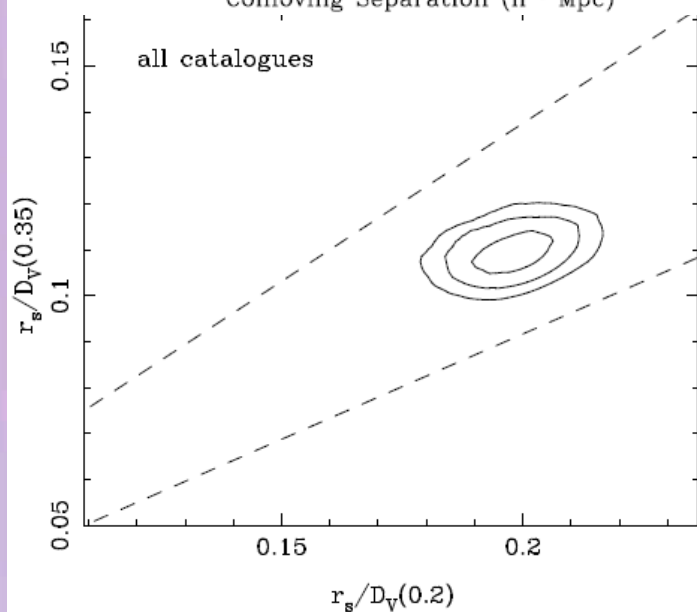


$$H(z) = h \sqrt{\Omega_m (1+z)^3 + \Omega_X \exp \left[ 3 \int_0^z \frac{1+w(z)}{1+z} dz \right]}$$

# 现有的BAO 探测



Eisenstein et al 2005



Percival et al 2007

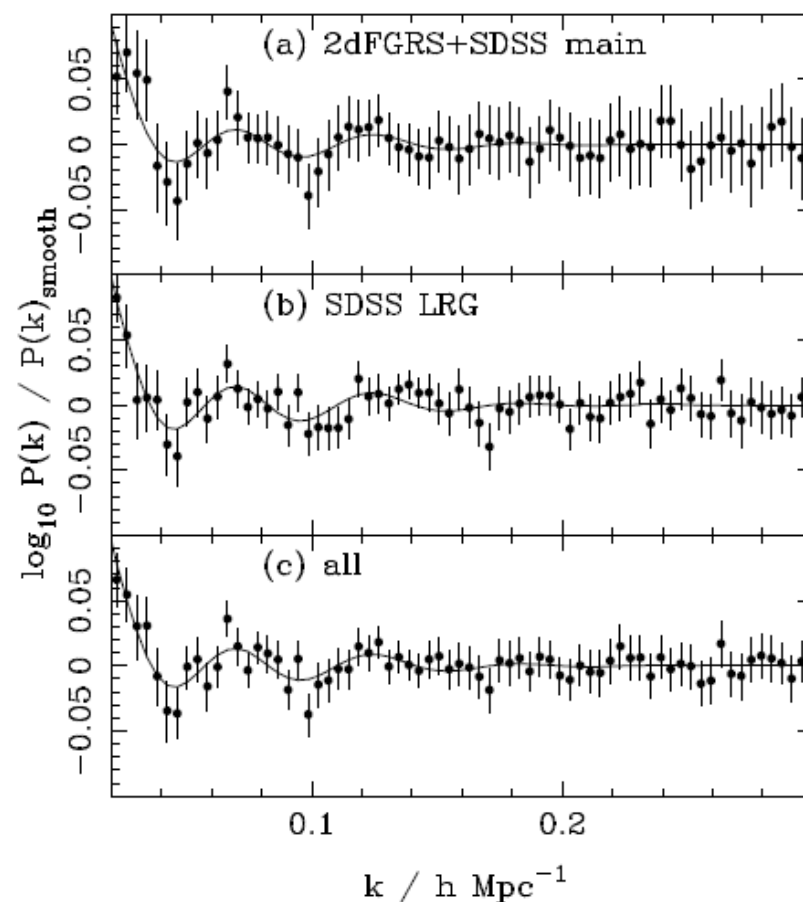
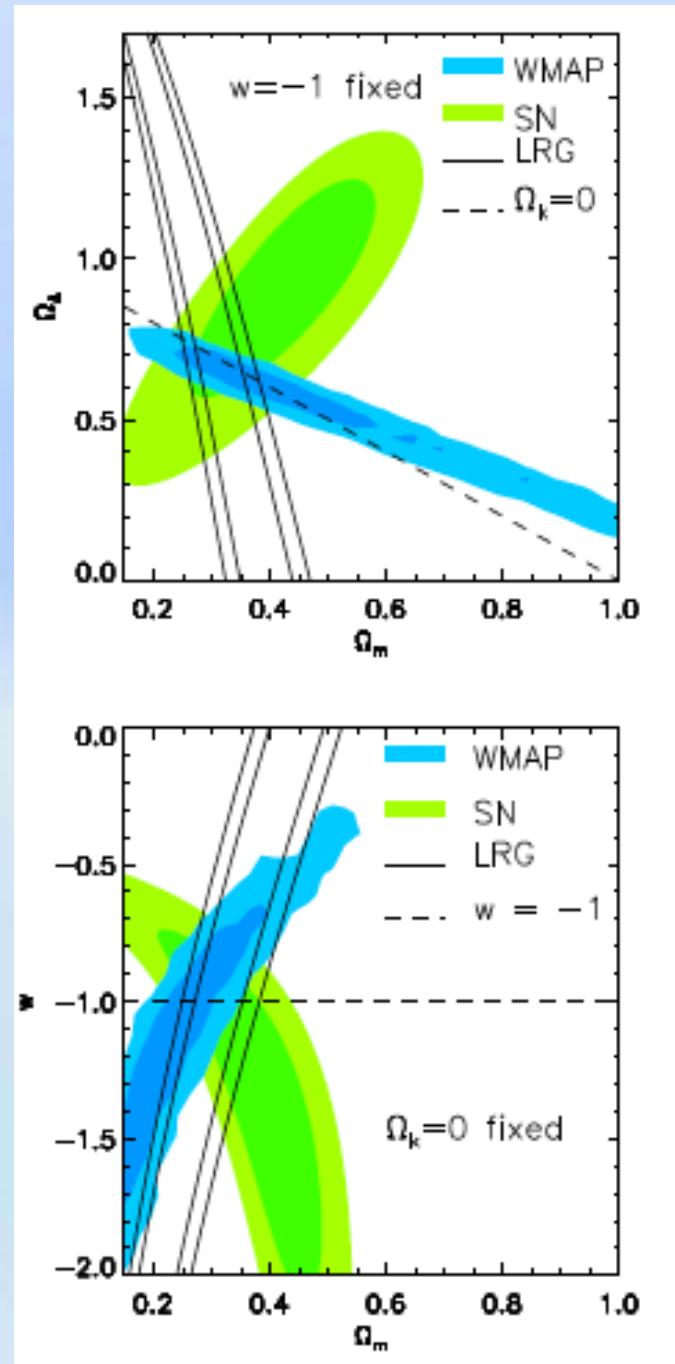
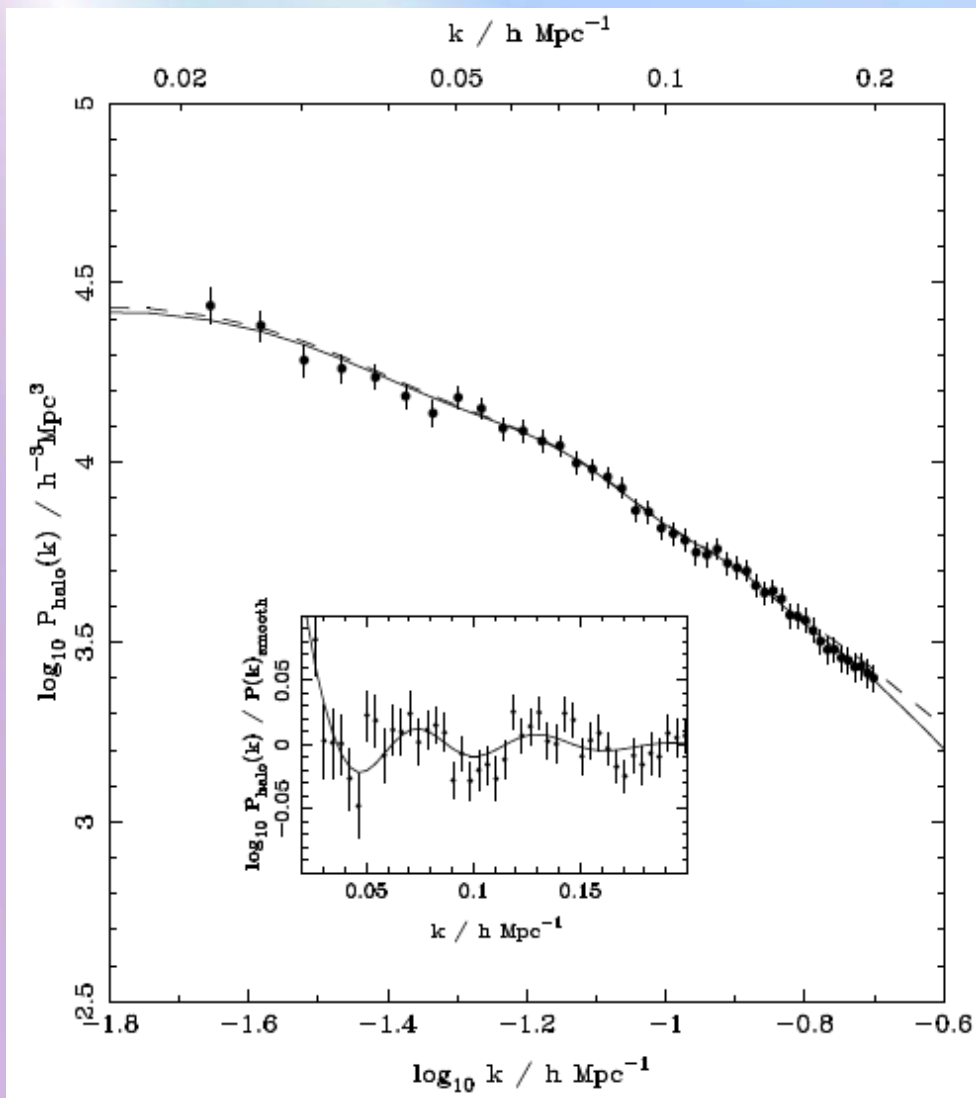


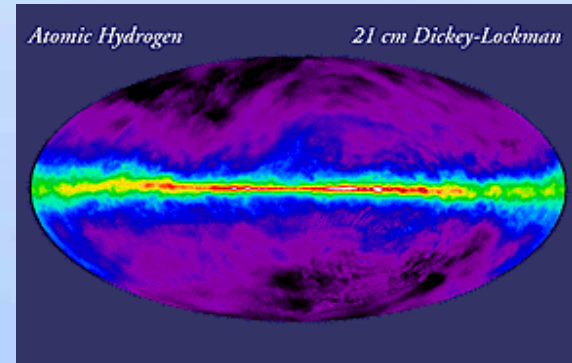
Figure 2. BAO in power spectra calculated from (a) the combined SDSS and 2dFGRS main galaxies, (b) the SDSS DR5 LRG sample, and (c) the combination of these two samples (solid symbols with  $1\sigma$  errors). The data are correlated and the errors are calculated from the diagonal terms in the covariance matrix. A Standard  $\Lambda$ CDM distance–redshift relation was assumed to calculate the power spectra with  $\Omega_m = 0.25$ ,  $\Omega_\Lambda = 0.75$ . The power spectra were then fitted with a cubic spline  $\times$  BAO model, assuming our fiducial BAO model calculated using CAMB, as described in Section (3). The BAO component of the fit is shown by the solid line in each panel.

# 宇宙学模型参数:

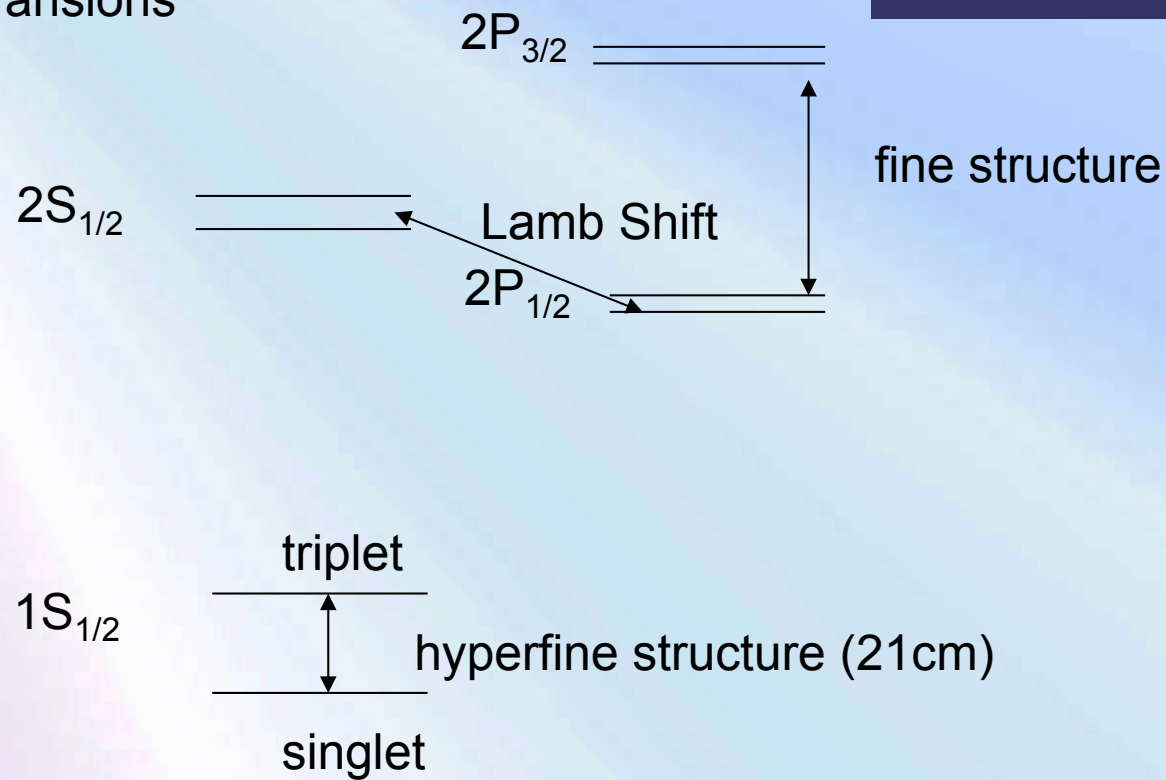


Reid et al. 0907.1659

# 21cm transition



atomic H transitions



# 射电观测红移21cm辐射

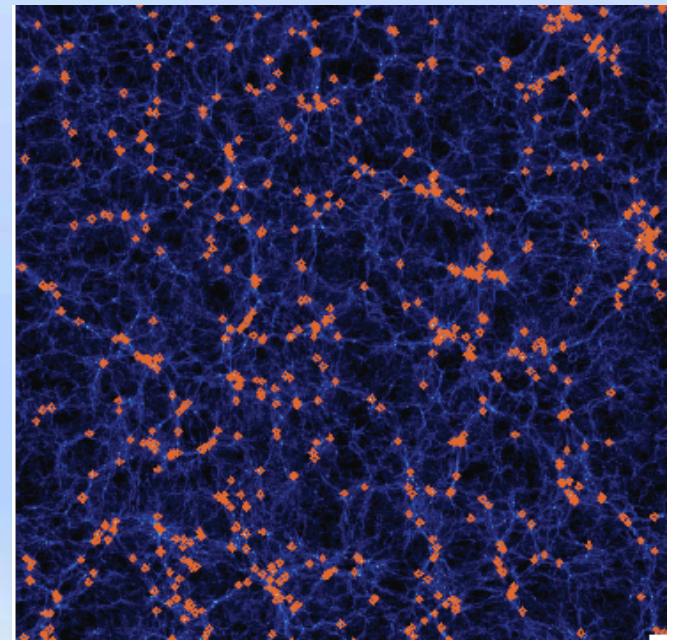
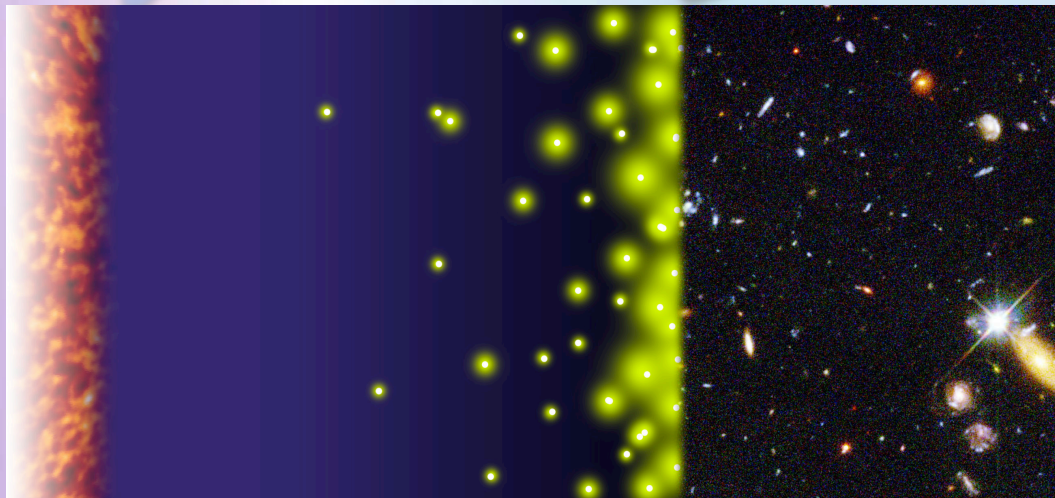
中性氢（未电离的原子氢）约占宇宙普通物质的  
3/4

中性氢可以产生 21cm 波长(1420MHz)辐射

宇宙中不同时刻辐射出的21cm 电磁波今天红移到了不同的波长

Recombination

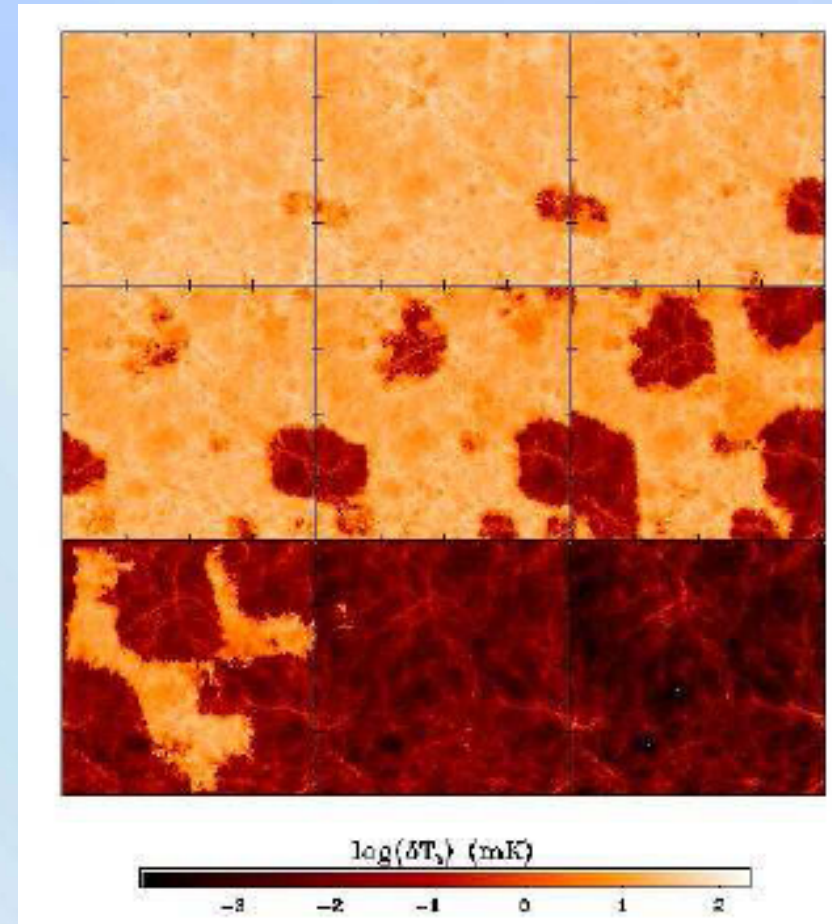
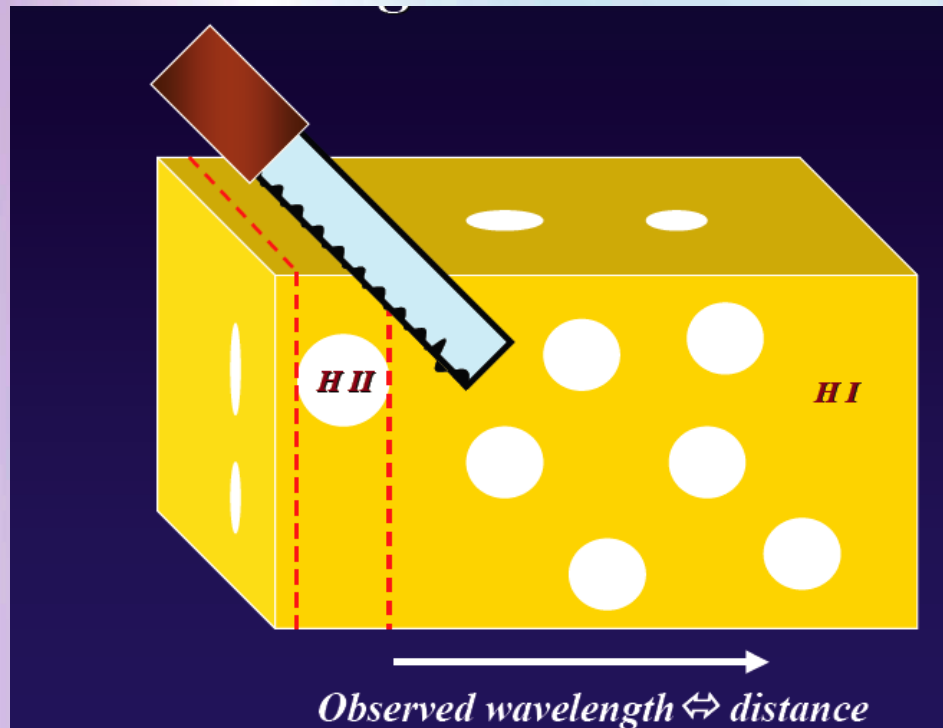
Reionization



星系作为物质分布的示踪物

# 21cm tomography

hyperfine transition of neutral H  
produce 21cm radio wave,  
redshifted to  $21(1+z)$  cm



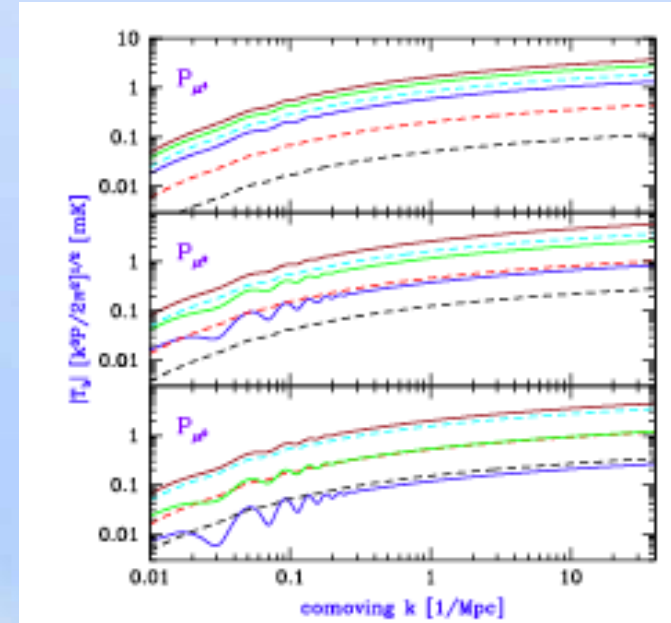
Furlanetto, Sokasian, Hernquist 2003

# The deep dark age

- Probe deep dark age ( $z \sim 200$ )?
- measure small scale power

number of independent modes:  
(Loeb & Zaldarriaga 2004)

CMB: only  $\sim 10^7$  modes



$$N_{21\text{cm}} \sim 3 \times 10^{16} (l_{\text{max}}/10^6)^3 (\Delta\nu/\nu)(z/100)^{-1/2}$$

- constrain angular diameter distance

**BUT:**

for  $z=200$ ,  $\nu=7$  MHz, difficult to detect from ground  
due to ionized layer of atmosphere, what to do?

Go to the moon!



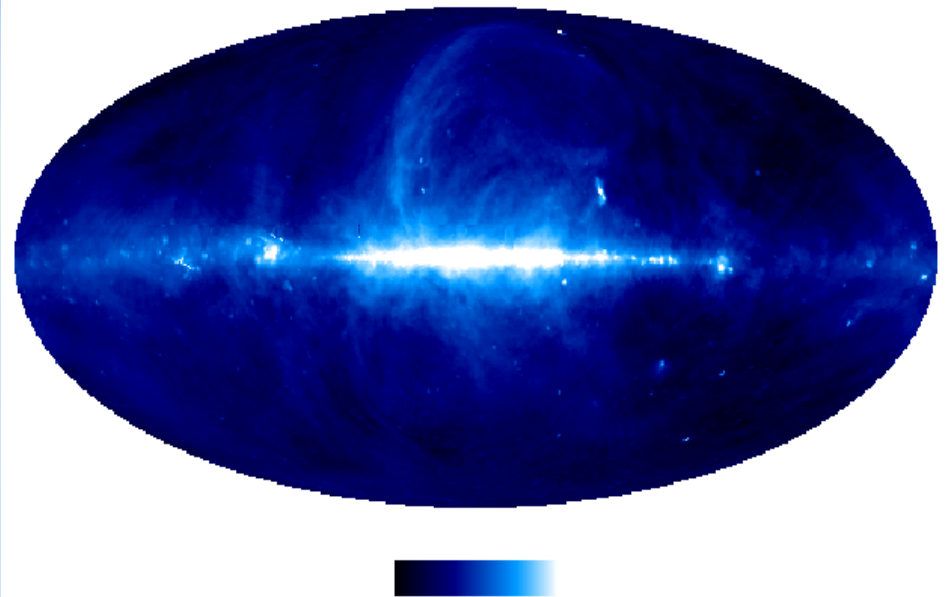


# 困难之处：前景噪声

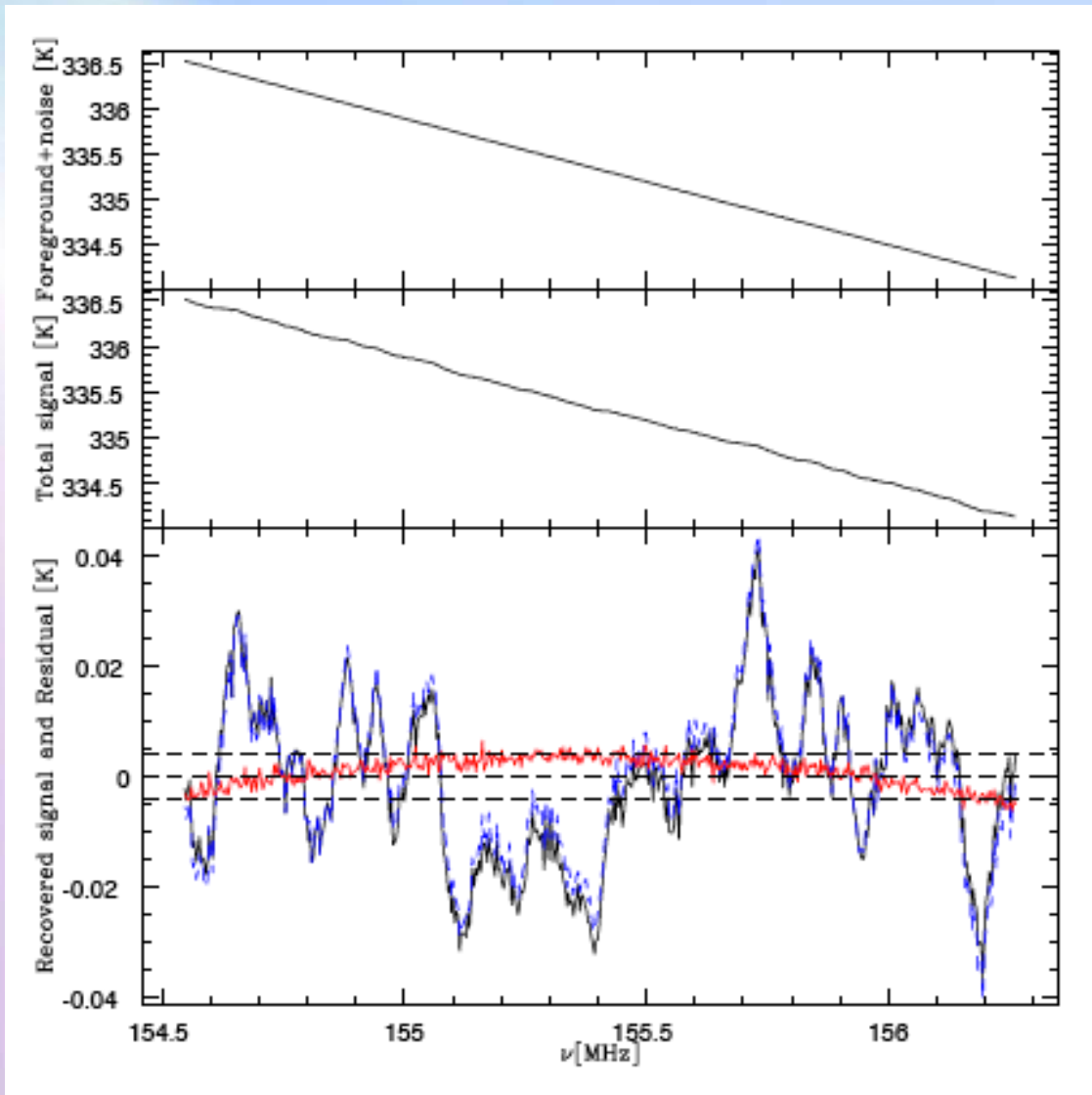
- 银河系同步辐射
- 银河系热辐射
- 射电点源（类星体和射电星系）
- 人工电磁干扰

$$T_{\text{galsyn}} \sim f^{-2.5}$$

Galactic Radio Emission



# 前景消除



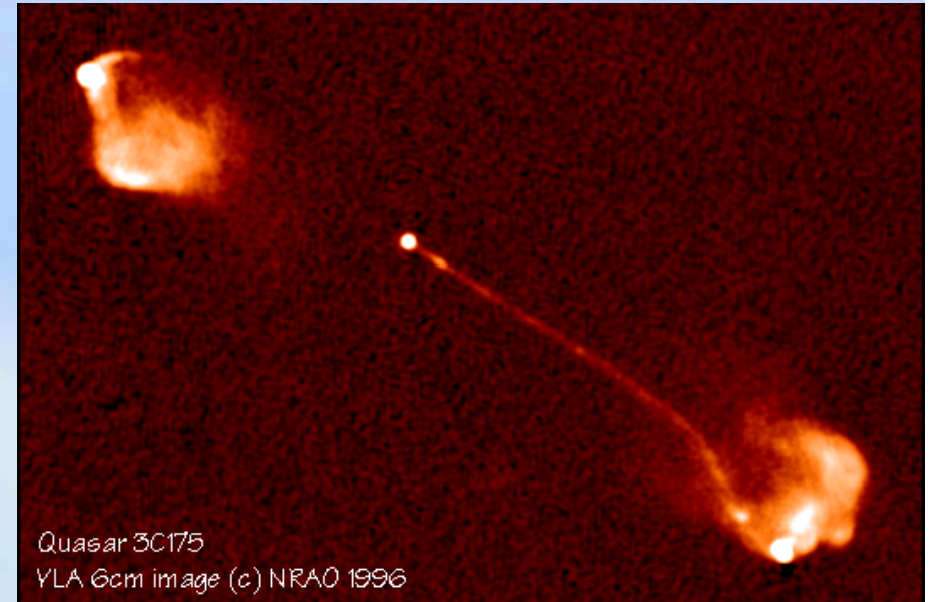
smooth  
foreground

foreground  
+21cm signal

recovered 21cm  
signal (blue) vs.  
real signal (black)  
and residual error  
(red)

simulated observation by X. Wang et al. (2006)

# 综合孔径成像 (Aperture Synthesis)



V: visibility  $\frac{\omega}{2\pi c} \mathbf{B} = (u, v, w)$

$$V(u, v, w) = \int A(x, y) I(x, y) e^{i2\pi(u x + v y + w \sqrt{1-x^2-y^2})} \frac{dx dy}{\sqrt{1-x^2-y^2}}$$

$$I(x, y) = \int V(u, v, 0) e^{-2\pi i(u x + v y)} du dv$$

Advance in digital electronics now enable us building interferometers with much larger number of elements

# 21cm projects for probing reionization

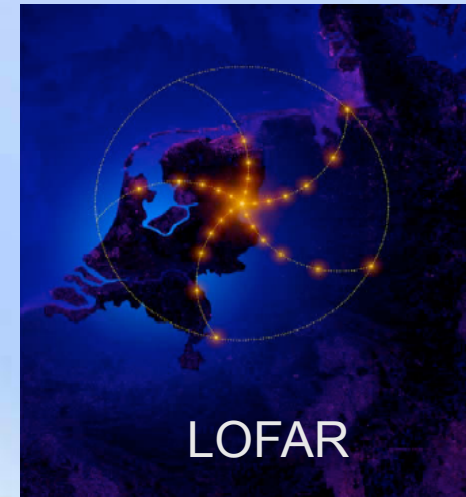
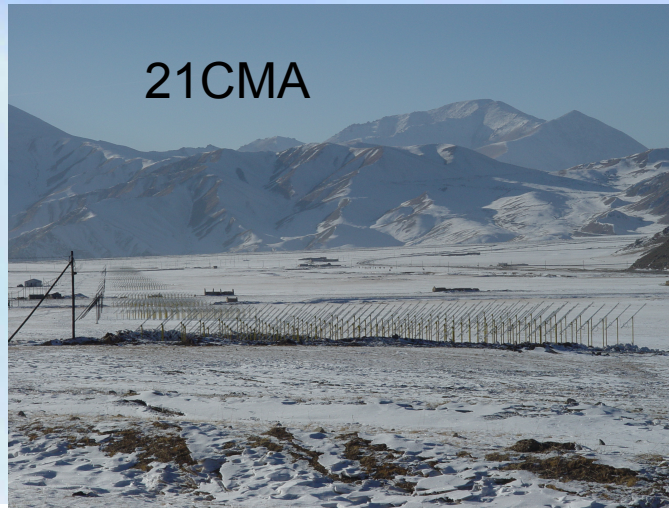
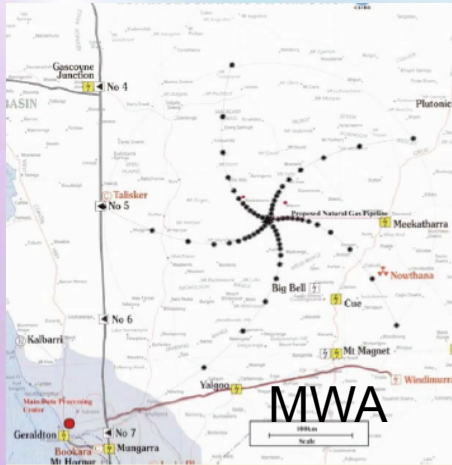
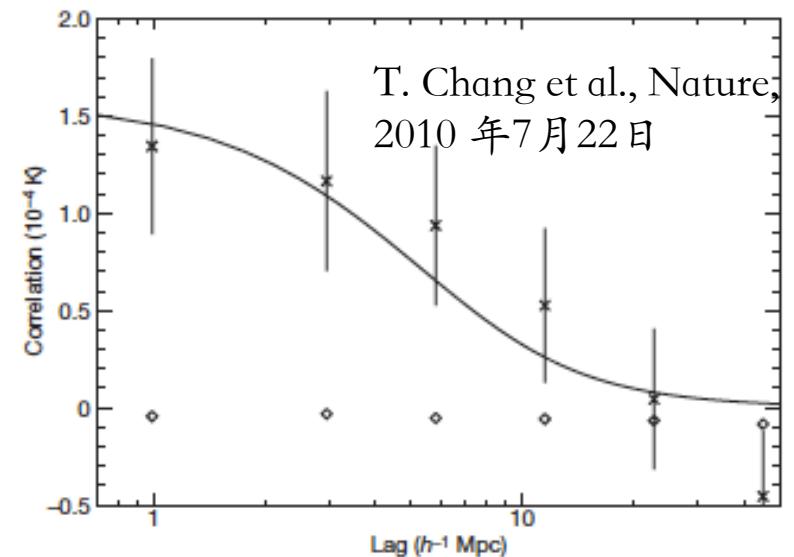
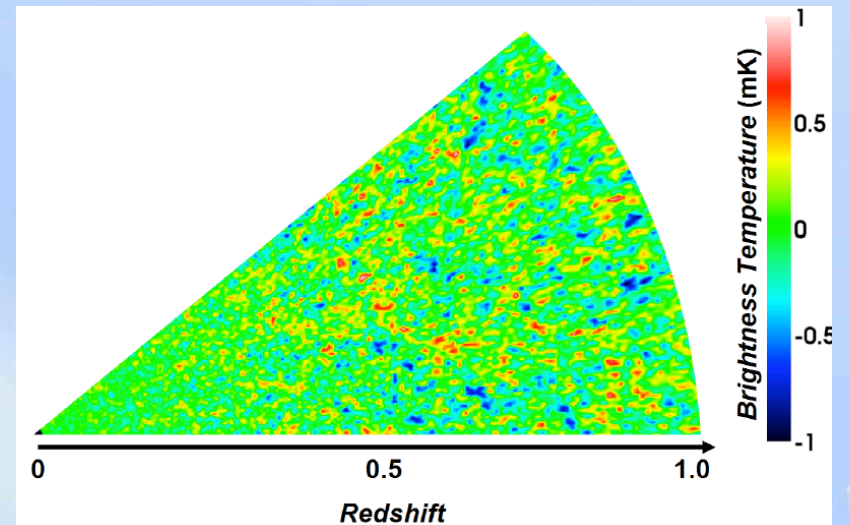


Table 1. EoR HI 21cm Experiments

experiment	site	$\nu$ range MHz	FoV deg	Area $m^2$	$B_{max}$ km	cost \$	date	Goal
SKA	?	100-200	15	$>1e6$	5km=50%	1G	2015?	Imaging
LOFAR	NL	115-240	10	$1e5$	2km=30%	70M	2007	PS/CSS
MWA/LFD	Oz	80-300	25	$2e4$	1.5	5M	2007	PS/CSS
PAST	China	70-200	10	$8e4$	10	?	2006	PS
PAPER	USA	125-175	50	100	0.2	small	2006	$\Delta T_{bg}$
MarkIV	Oz	100-200	100	1	0	small	2006	$\Delta T_{bg}$
VLA-VHF	USA	178-204	4	$1.3e4$	1	0.1M	2005	CSS (PS)

# 21cm 映射观测BAO

- 在大尺度上，21cm辐射强度正比于物质密度。通过观测不同波长的辐射，可以获得不同红移的21cm辐射分布
- 由于我们感兴趣的是物质大尺度结构分布，因此没有必要分辨单个星系，而可以测量一定体积内的中性氢总量，这就是所谓的21cm映射(21cm intensity mapping)方法
- 对于观测暗能量来说，红移0—2.5间的观测最为有用，因此观测频率为400MHz-1400MHz



# 天籁项目 (Tianlai project)

与 Jeff Peterson (CMU), 彭威礼 (Toronto), Reza Ansari (Paris-Sud) 等合作, 在中国建造一个联合实验项目, 对基本原理和关键技术进行检验

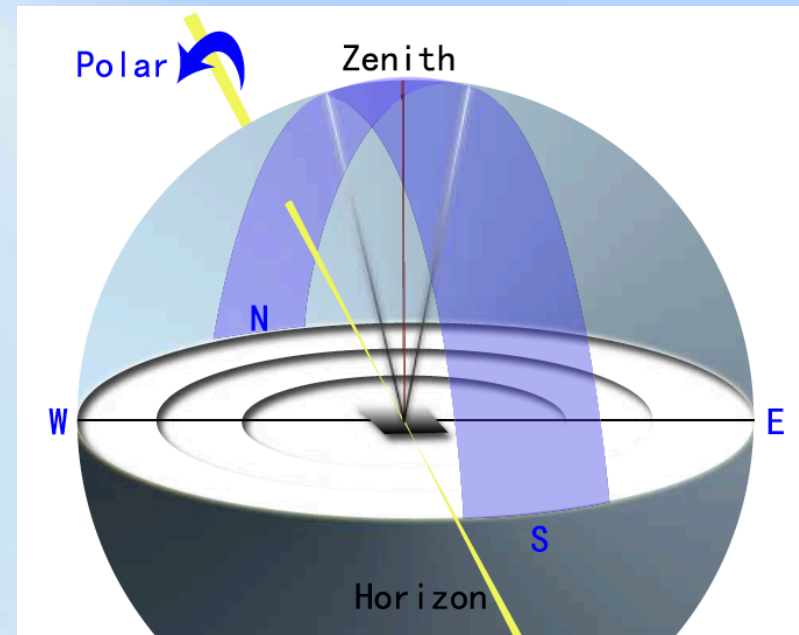
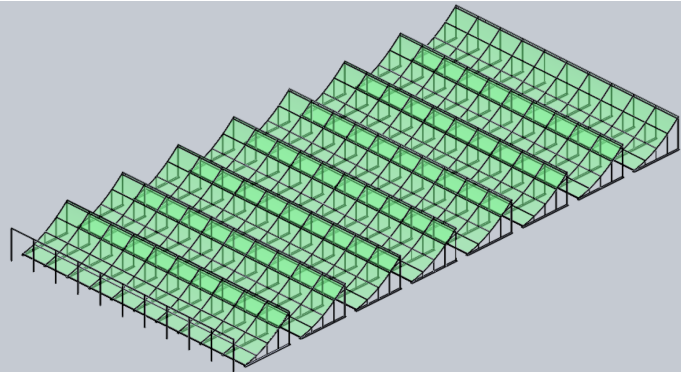
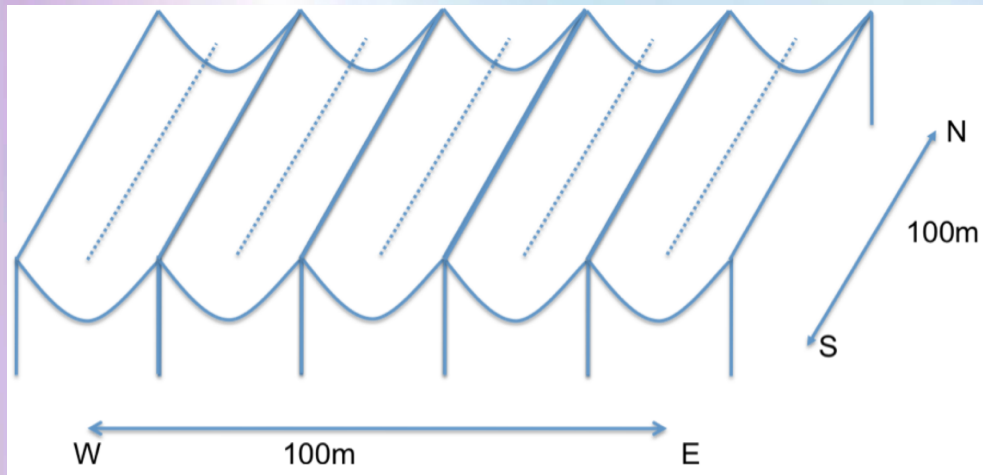


Science 网站对此进行了报导

# 实验设想

主要特点:

- 柱面反射天线
- 约2500个双极化接收机单元，数量远远超过所有现有的天文射电阵列（例如，美国VLA只有27个单元）



# 合作组情况

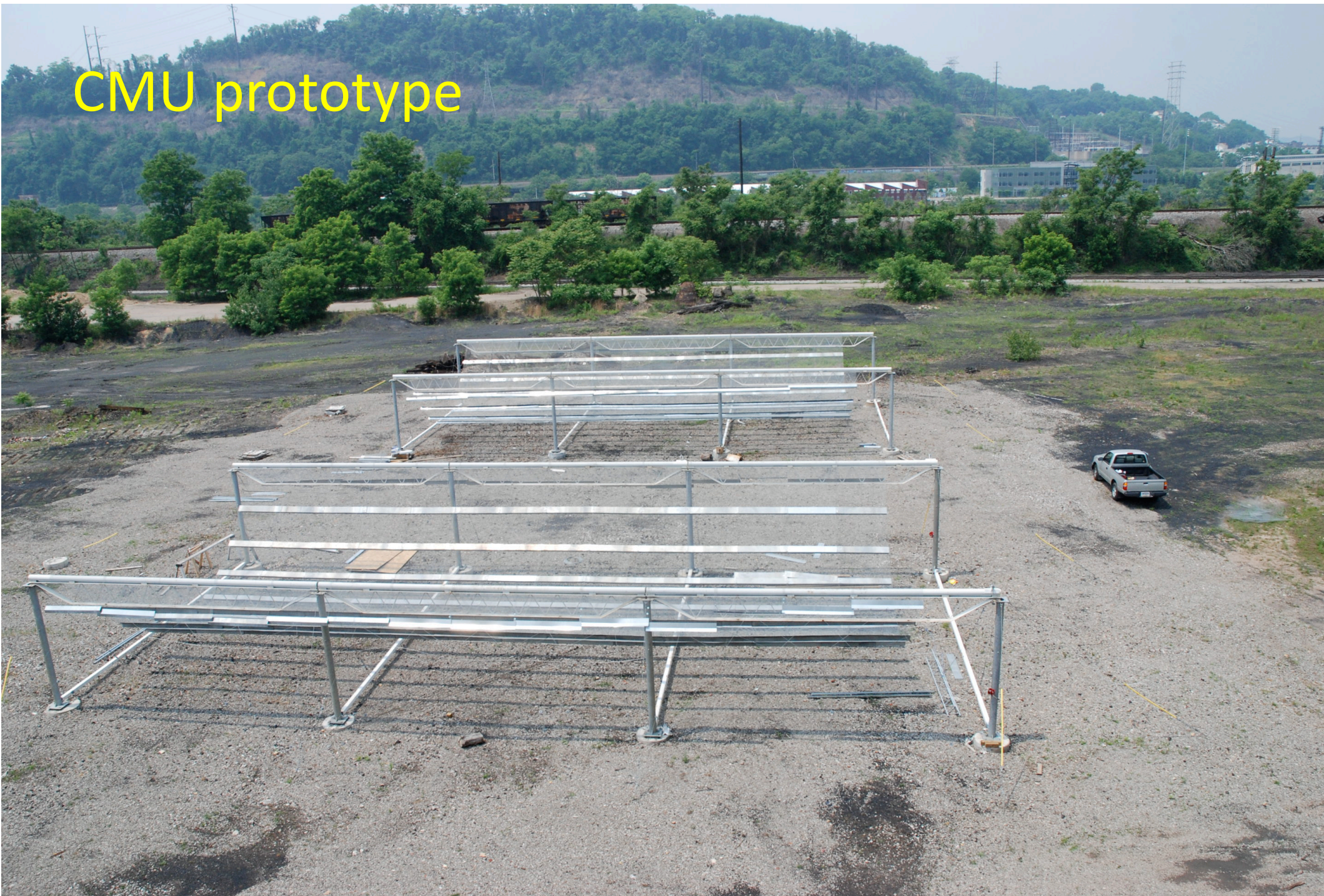
国际:

Jeff Peterson (CMU), Ue-Li Pen (CITA), Sigurdson (UBC), Ansari (In2p3), McGinnis (Fermlab)...

国内: 国家天文台、中国电子科技集团公司54所、上海天文台、北京大学、国防科技大学、杭州电子科技大学、自动化所等



# CMU prototype







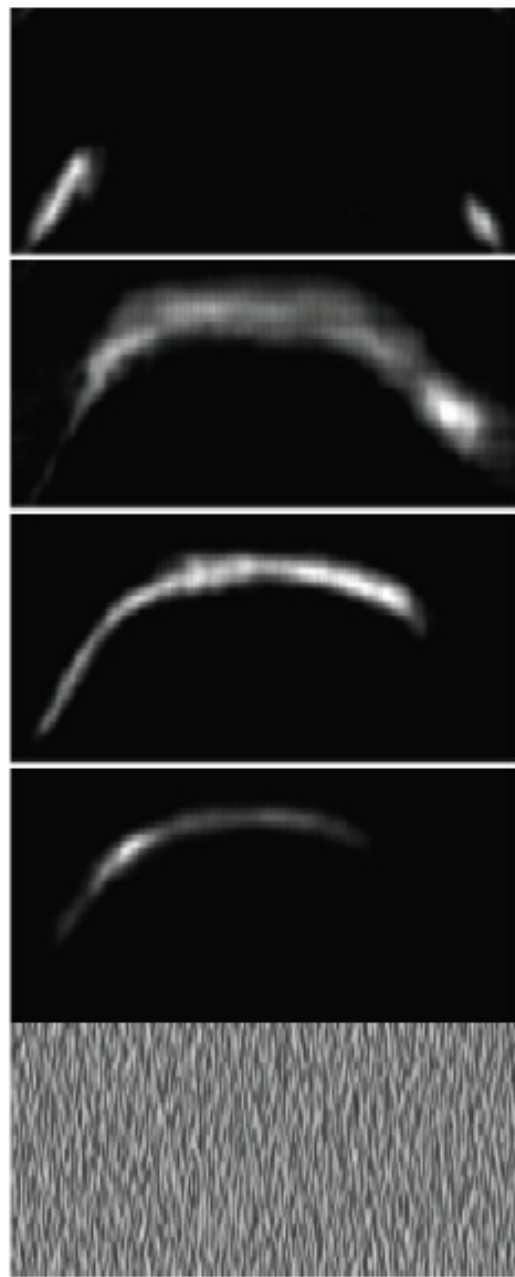
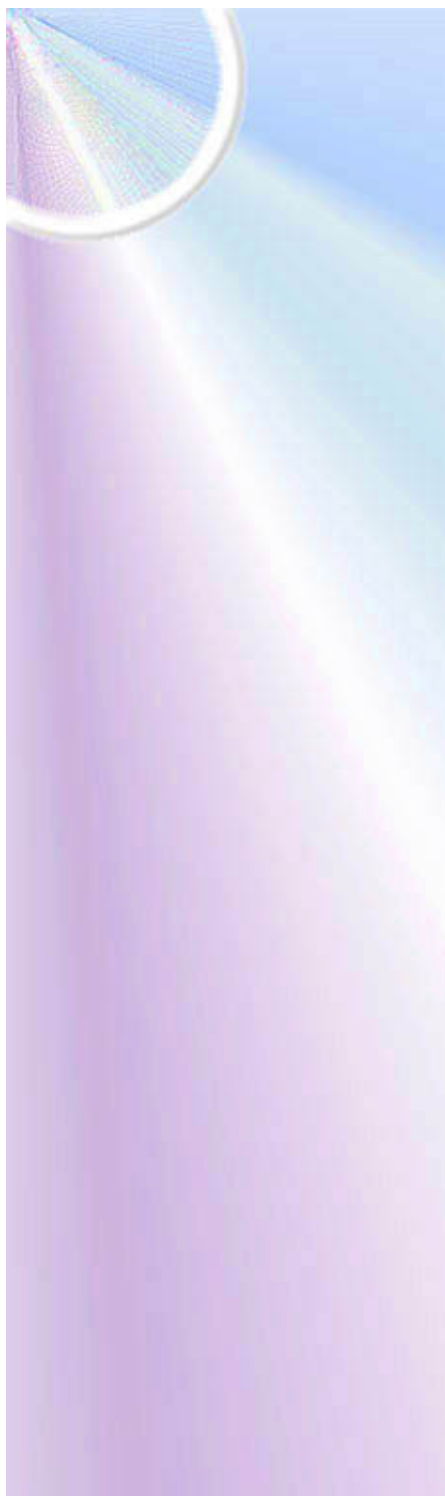


图11. 利用 Pittsburgh 柱形天线模型观测到的银河系 21cm 辐射。各图分别对应不同的频率（速度），已减去前景。最下面一幅图对应的是银河系以外，中性氢含量远低于银河内，因此没有看到 21cm 辐射。

# 先导实验

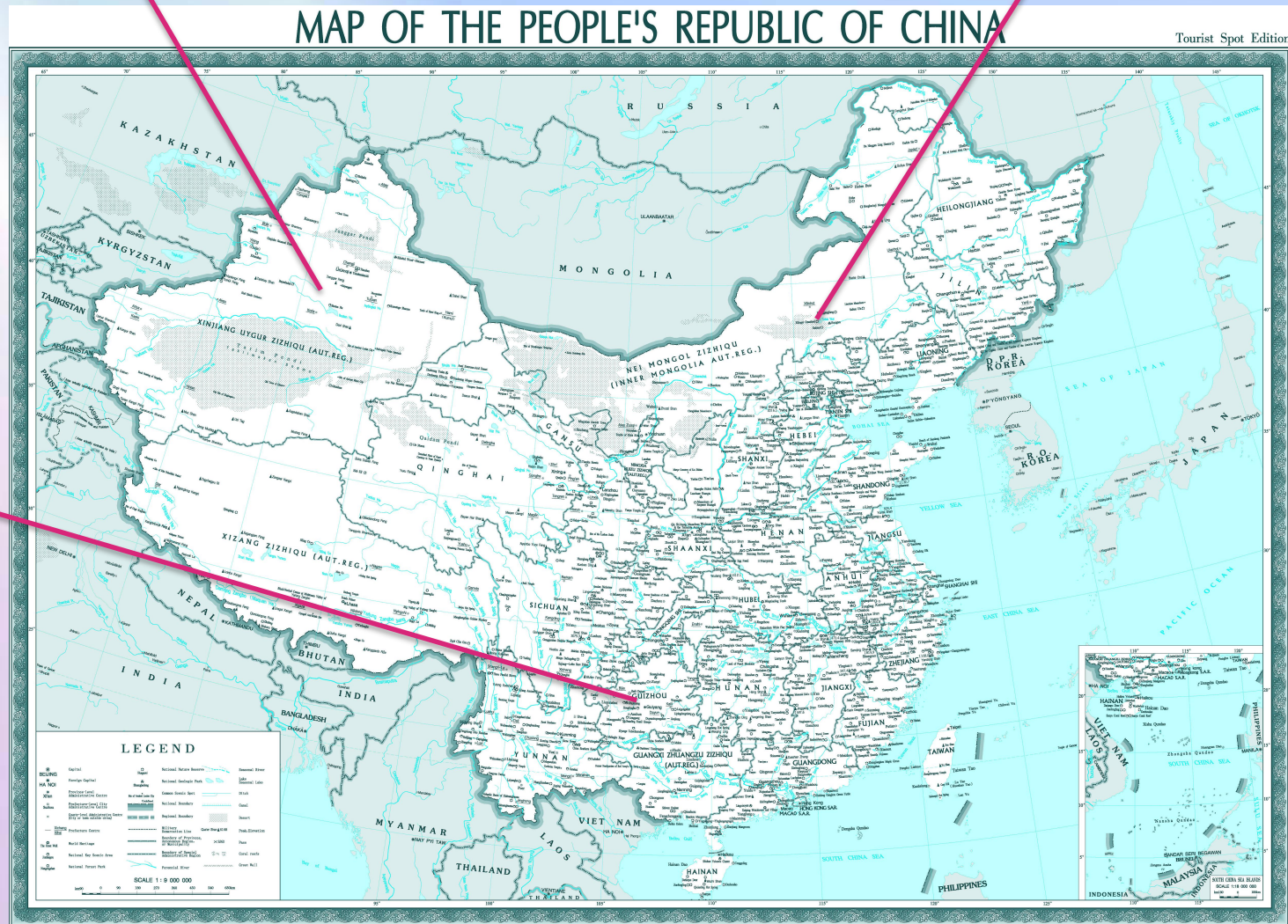
- 首先进行一个小规模的前导实验，检验基本原理、试验不同的设计，减小全规模实验的风险
- 3x50mx15m 柱面
- 4路或16路合路以减少信号处理的费用
- 预计进行2—3年（但也有可能更长）
- 全规模实验时可以选用最新的技术
- 先导实验+整个实验: 5-8 years

# 可能的站址

Xinjiang

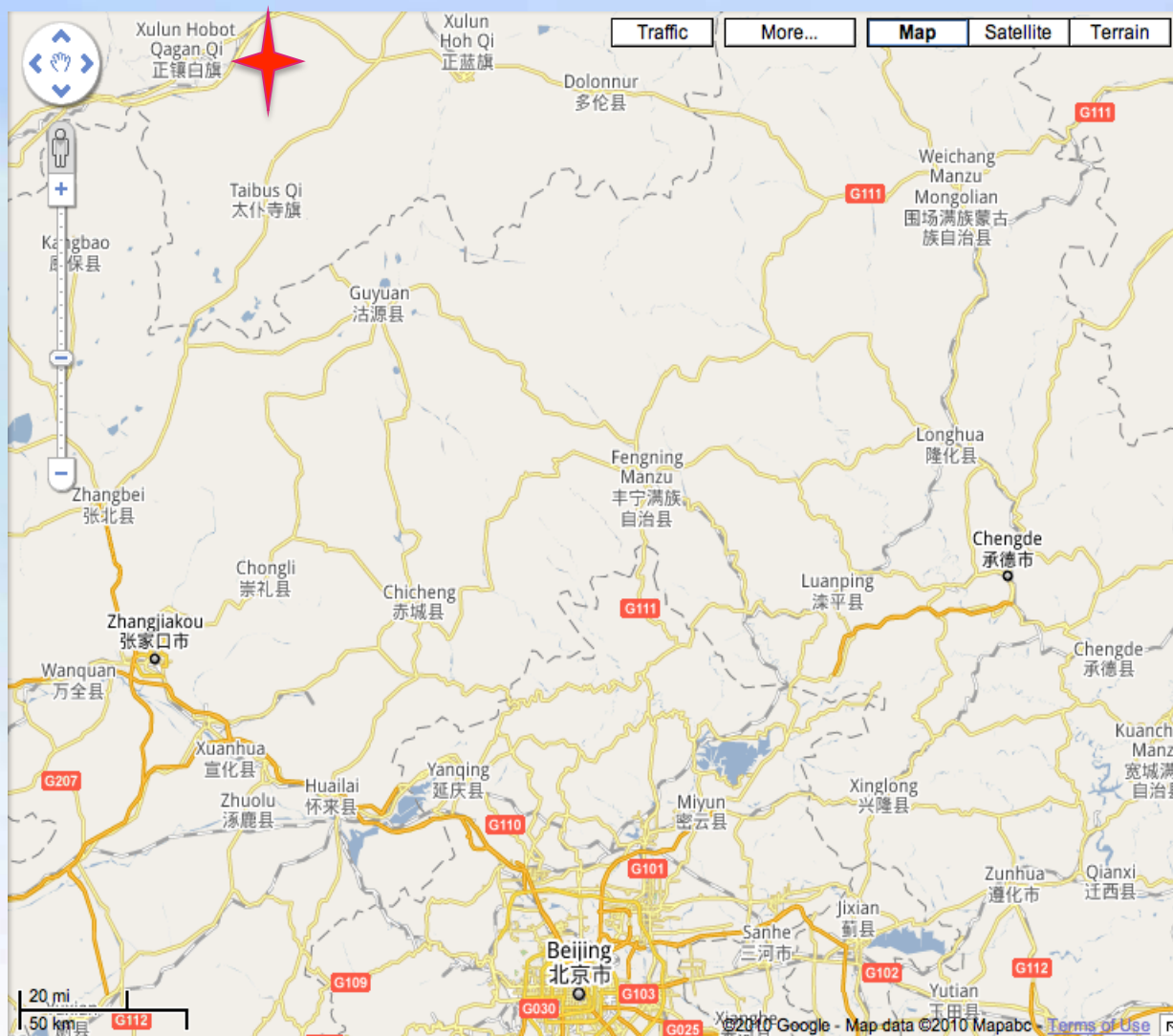
Inner Mongolia

Guizhou

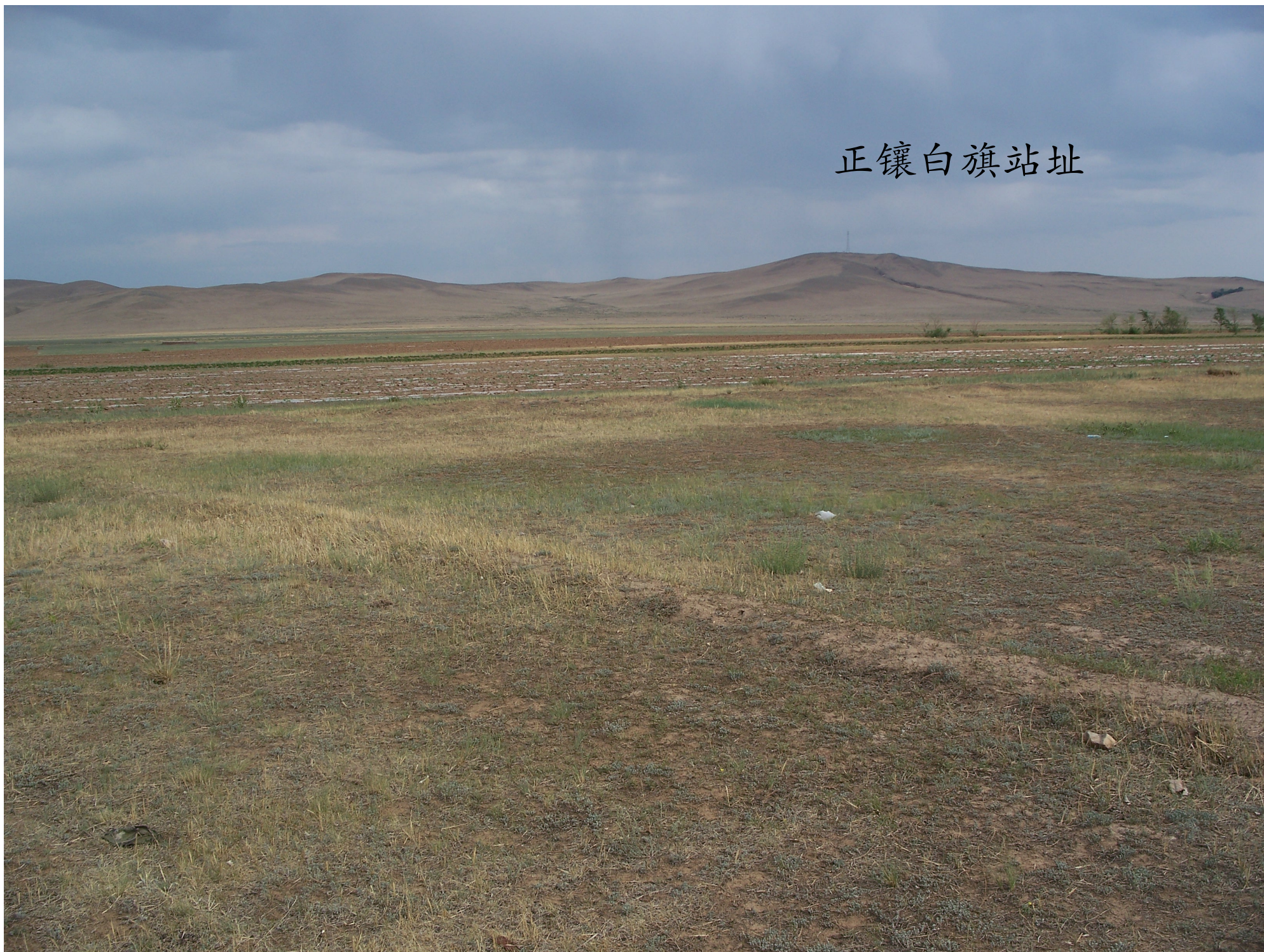


# 站址

- 要求：电磁环境好，避免手机和电视干扰
- 交通、电力供应方便，最好已有天文或其他科研单位支撑
- 初步考虑内蒙正镶白旗（国家天文台射电日像仪站址）作为先导实验站址，同时进一步寻找电磁环境更理想的站址

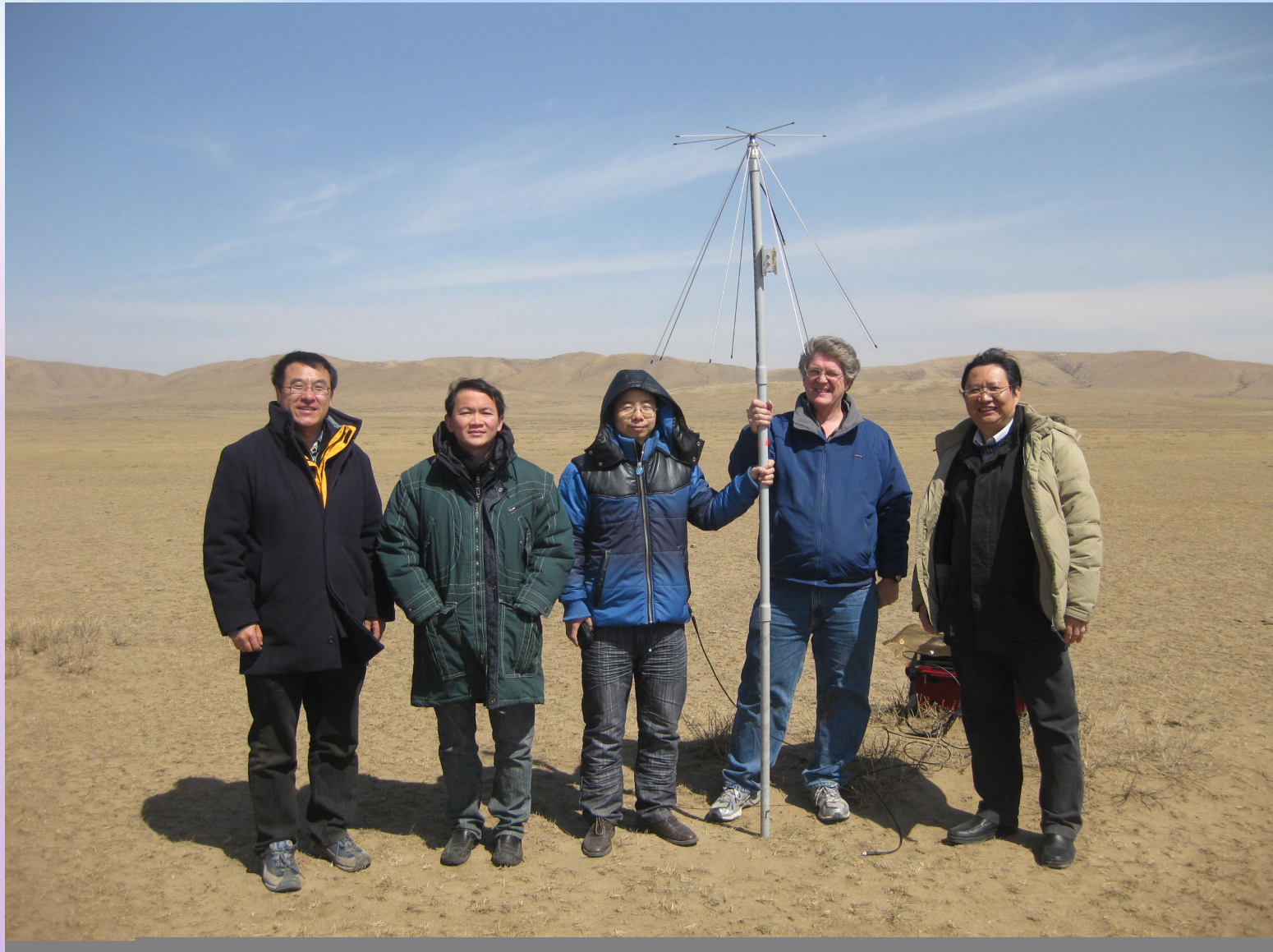


正镶白旗站址

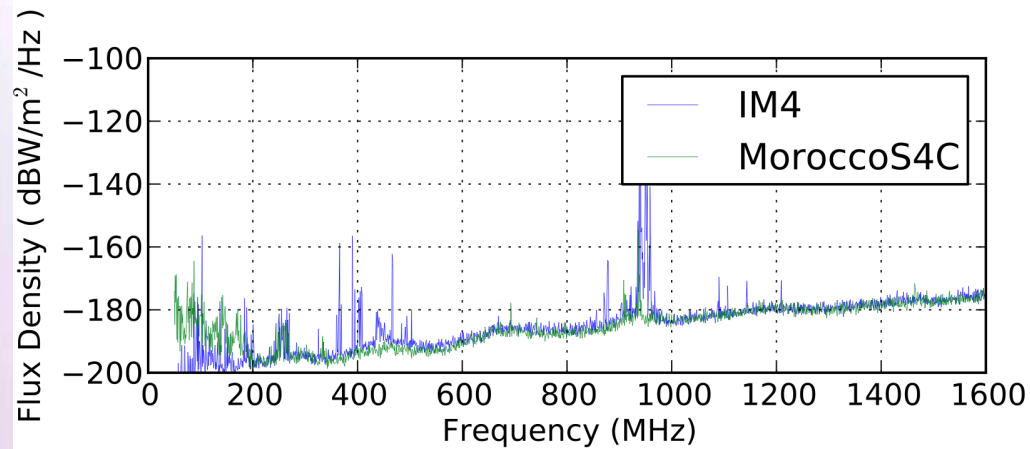
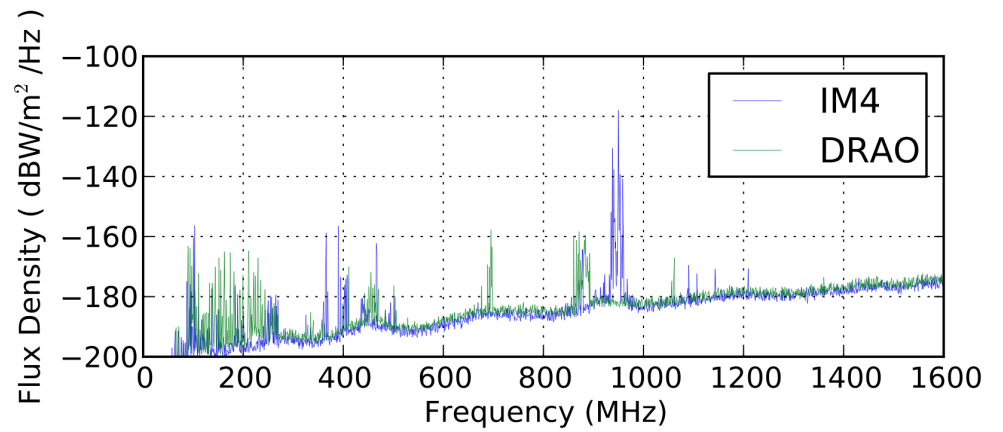
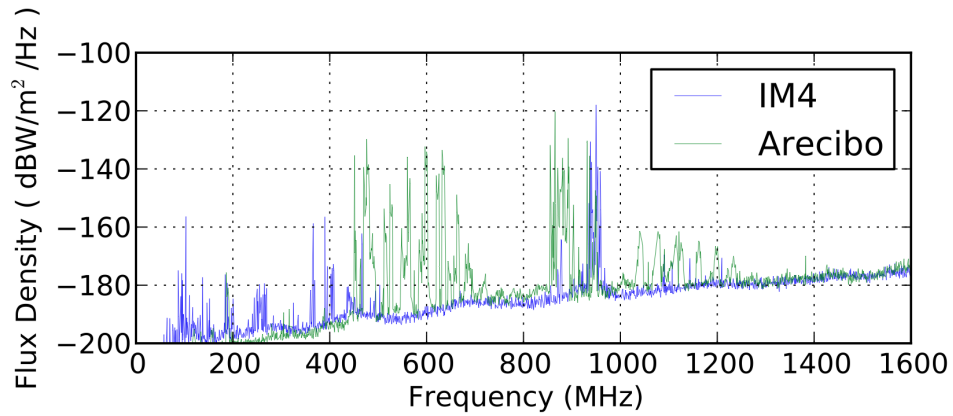




# 2010年4月 彭威礼和Jeff Peterson 考察明图安站址



# 站址电磁环境比较

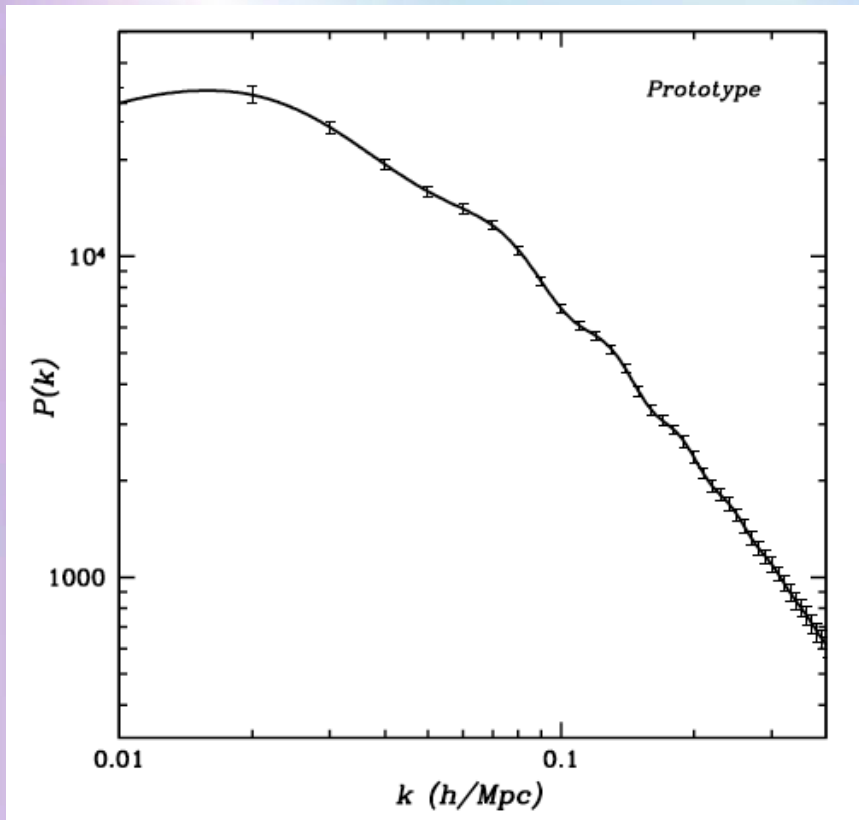


# Xinjiang Site

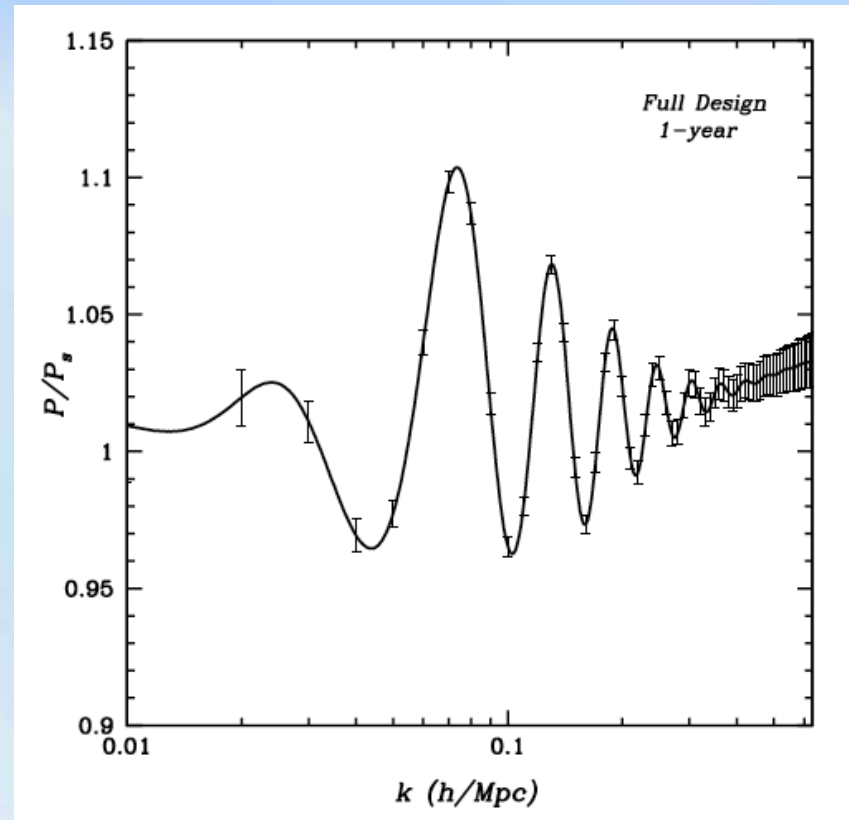


# 信噪比分析-功率谱

$$\frac{S}{N} = \sqrt{\frac{4\pi k^2 dk V_{\text{survey}}}{2(2\pi)^3}} \frac{P_{\text{HI}}}{P_{\text{HI}} + \left[ \frac{(gT_{\text{sky}} + T_a)}{gT_{\text{sig}} \sqrt{t_{\text{int}} \Delta f}} \right]^2 V_R + \frac{1}{n}},$$

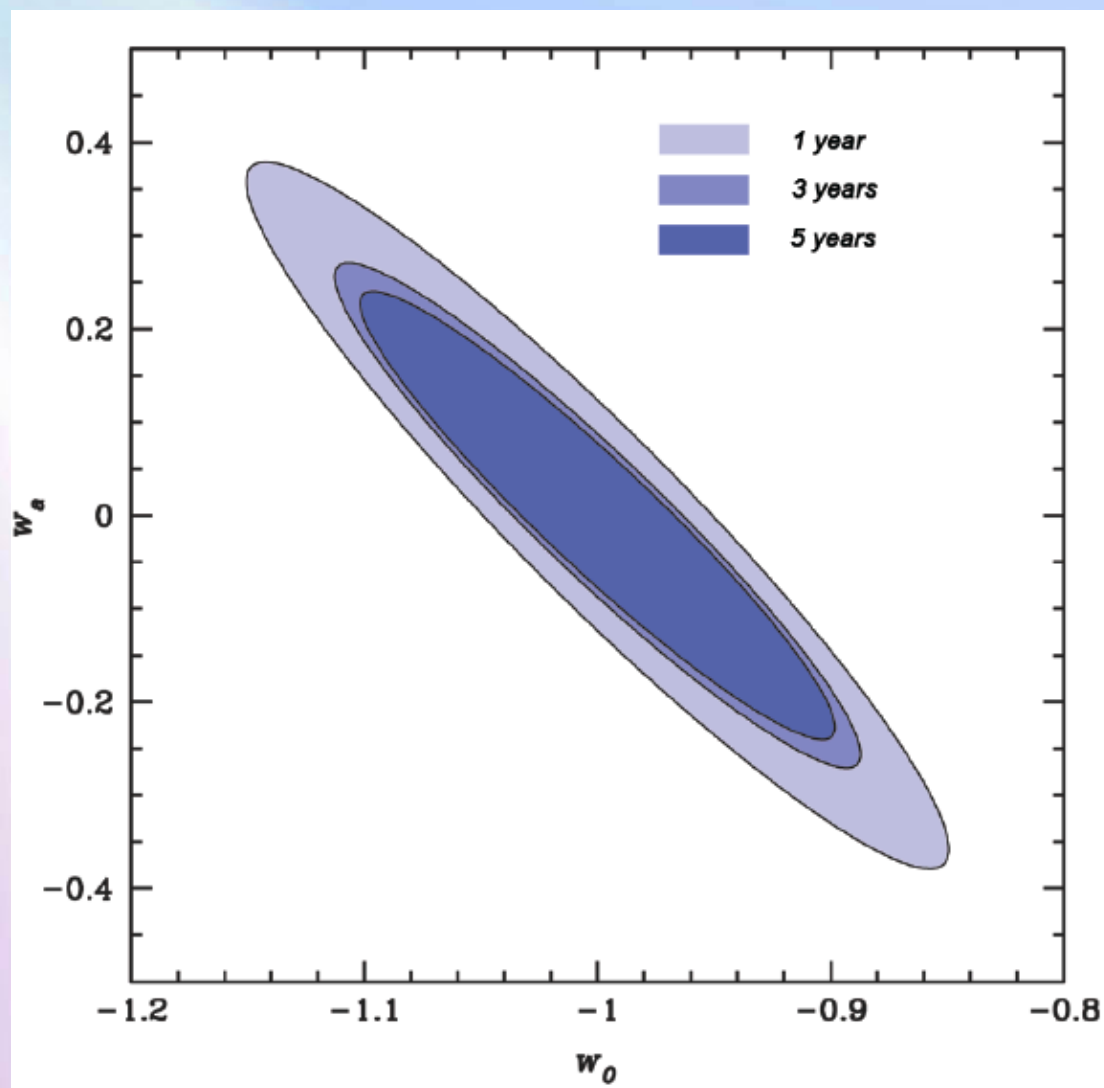


先导实验1年观测的功率谱精度



全规模实验1年功率谱BAO观测精度

# 全规模实验测量暗能量状态方程精度



# 天籁项目当前情况

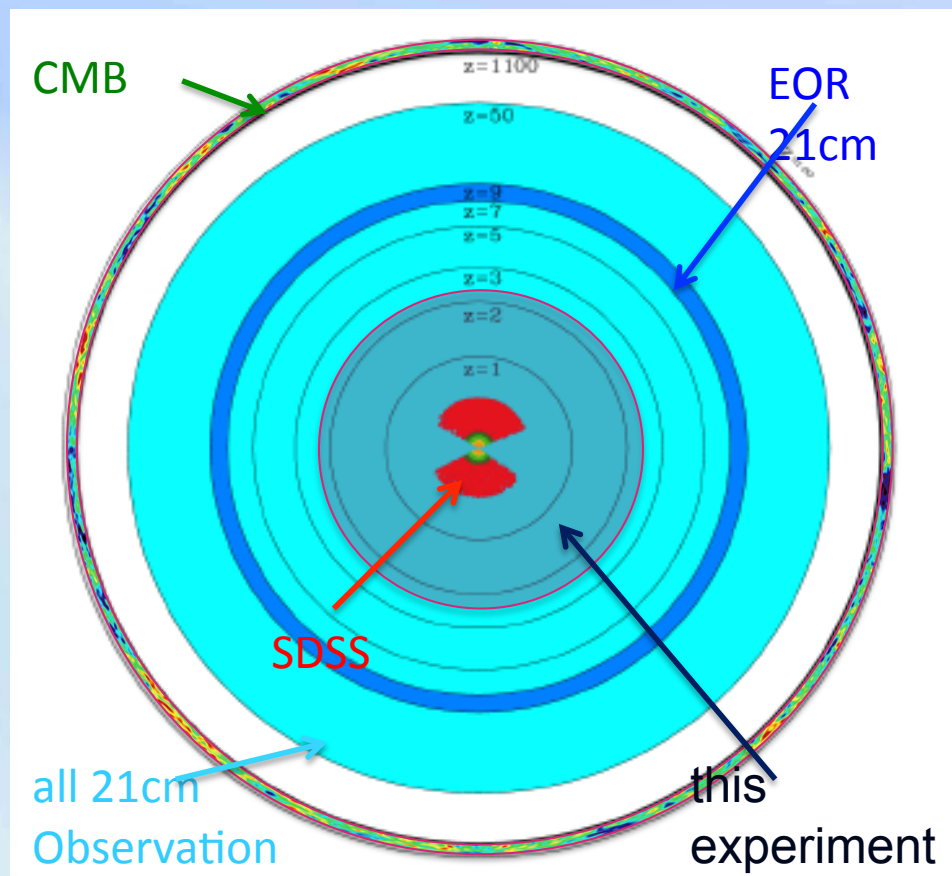
目前已得到国家天文台和北京大学高能物理中心的启动经费资助，研制试验天线，利用国外接收机开展联合实验


下一步：做好天线，开展数据处理研究，同时国内也要开始相关接收机的研制

希望这一项目得到大家更多的关心和支持，也欢迎感兴趣的同志参予研究

# 科学意义

- 中国主导的暗能量实验，没有国内无法做的技术
- 可在国内地面进行
- 与国外基本同时起步，10年左右完成（5年预研，5年全规模实验），有竞争力



A night sky photograph showing the Milky Way galaxy. The galaxy's core is visible as a bright, hazy band of light stretching diagonally across the frame. The foreground on the right side shows a portion of a satellite dish antenna, which is illuminated from below, creating a warm glow. The background is filled with numerous stars of various colors, including blue, white, and red.

谢谢



# 检验引力

- ❖ 结构增长与膨胀历史是否一致

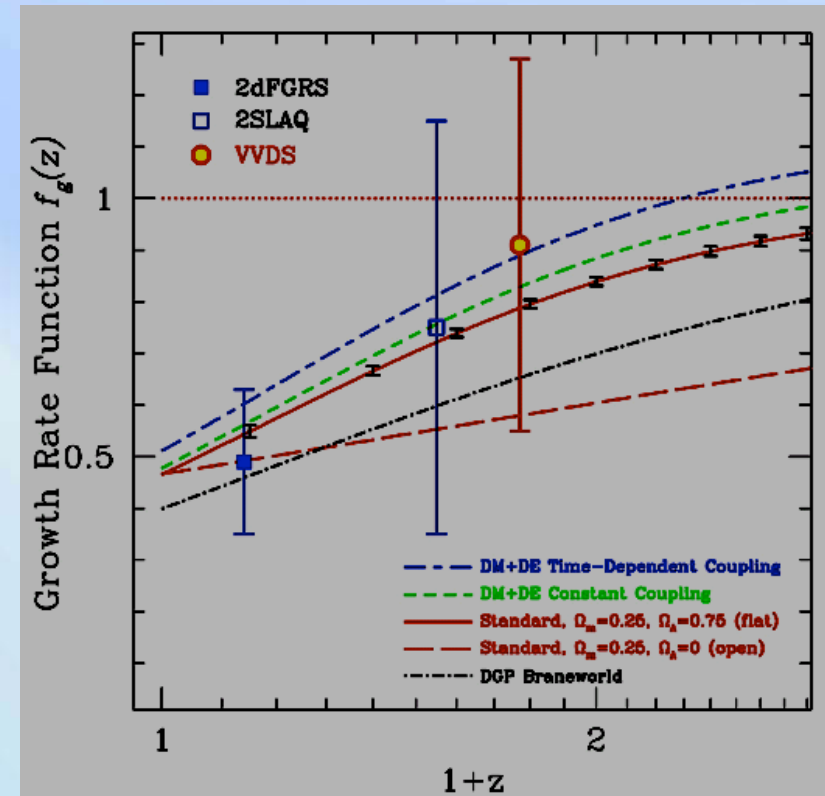
$$\frac{d^2\delta}{da^2} + \frac{d\delta}{da} \left( \frac{dH/da}{H} + \frac{3}{a} \right) - \frac{3}{2} \frac{\delta}{a^2} \frac{\Omega_0 H_0^2}{H^2 a^3} = 0$$

- ❖ 检验Poisson 方程

$$\nabla^2(\Phi - \Psi) = -8\pi G\bar{\rho}\delta$$

gravitational lensing

peculiar velocity



Guzzo et al. 2008